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LASER GYROSCOPES

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16. Abstract

A popular scientific description is given of the principle of operation, design, and basic characteristics of gyroscopic devices and lasers and the principle of operation of the laser gyroscope. A brief survey is made of the applications of laser gyroscopes in navigational systems. The material on which the pamphlet is based has been taken from published Soviet and foreign sources.

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A. D. Bogdanov

Introduction /3*

The vigorous development of technology in recent decades is indissolubly linked to improvement in various systems for control of moving objects. The control systems of torpedoes, seagoing ships, aircraft, missiles, and space vehicles are inconceivable without gyroscopic instruments.

A gyroscope is generally the sensing element in such systems. The gyroscope is a dynamically balanced body of rotation which rotates at high speed around a shaft secured in a frame and which has at least one fixed point.

The gyroscope was first put to practical use in 1852, when the French scientist L. Foucault employed a gyroscope to confirm his experiment with a pendulum proving the rotation of the Earth. The first gyroscopes were characterized by large errors caused by the lack of balance of individual components of the instrument, the inertia of the frames, gaps in connections, uneven friction in the universal joint supports, and so forth.

These are the factors which represent the main sources of error in the majority of modern gyroscopic devices as well, although the errors themselves have become much smaller.

More than 100 years have passed since the time of Foucault's experiment, and all of this period in the development of gyroscopic instruments and systems has been one of earnest effort to increase the accuracy of their operation.

The errors of gyroscopic instruments have decreased constantly, but increasingly rigid requirements have also been set for the accuracy of maintenance of the position of a rapidly rotating body in space.

Since the errors of the instruments decrease with increase in the mass of the gyroscope rotor and its rotational speed and with decrease in friction in the suspension shafts, designers have been forced to created massive rotors and increase their rotational speed to tens of thousands of revolutions per /4
minute. They began to place the rotor shafts in bearings of widely varying design. Ball and roller bearings were perfected, the suspension shafts began to be secured in very hard supports of precious and semiprecious materials, various lubricants were used, and gyroscopes with air cushioned bearings have even been produced.

*Numbers in the margin indicate pagination in the foreign text.

Float gyroscopes have become fairly common. In instruments of this design the pressure of certain of the axes of rotation of the gyroscopes on the bearings has been reduced to the minimum by immersing the rotor housing in a liquid.

As a result of all these developments, the best electromechanical gyroscopes (they may also be termed inertial gyroscopes) have a "drift" of no more than 0.001° per hour.

The "drift" of a gyroscope is to be understood to mean the angular velocity of precession resulting from the action of friction forces in the suspension bearings, the imbalance of the gyroscope rotor, and so forth. A slight further decrease in "drift" renders gyroscopic devices considerably more costly. But even these very expensive instruments today do not satisfy the builders of spaceships and other modern equipment.

Many other deficiencies are inherent in gyroscopic instruments having a rotating rotor. In particular, they require a considerable amount of time to be brought into a state of complete readiness, they cannot withstand great overloads, and they consume a large amount of electric energy.

Gyroscope builders, having now begun a search for new instrument design principles, are attempting to dispense with the use of a heavy mechanical rotor. Vibrational gyroscopes (based on the tuning fork), gyroscopes using electrostatic and electromagnetic rotor suspensions, corpuscular gyroscopes, and so forth have now been produced and are undergoing further development. It is too early to tell where the testing of such gyroscopes will lead, but scientists are continuing their search.

As the result of the vigorous development of a new field of human knowledge, quantum electronics, there has been created a gyroscopic instrument of a new type, the laser gyroscope, and we invite the reader to make its acquaintance.

1. Principle of Operation, Structure, and Basic Characteristics of Gyroscopic Instruments and Lasers /5

In the writing of this pamphlet it has been assumed that the reader is familiar with the basic concepts of the theory of gyroscopic instruments and quantum electronics. The author nevertheless feels it to be necessary to recapitulate certain theoretical conclusions on which all of the following material is based.

The principles of gyroscope theory were elaborated by L. Euler, L. Foucault, Ch. Lagrange, S. Kovalevskaya, and other scientists of the eighteenth and nineteenth centuries. Soviet scientists have also made a significant contribution to development of the theory of gyroscopes.

In our days gyroscopic instruments and systems are employed in widely varying fields of engineering: for automatic control and navigation, for stabilization of weapons on warships and tanks, in the mining and petroleum industries for driving shafts and tunnels, in the drilling of oil wells, and so forth.

Gyroscopic instruments are used to determine the direction of the true meridian and the amount of deflection from the true vertical, and to measure angles of deflection, angular velocities, and the acceleration of a maneuvering object.

Gyroscopic instruments are among the basic elements of inertial guidance systems used to control the majority of foreign ballistic missiles. Gyroscopic instruments have assumed particular importance in navigation systems.

1.1. Physical Principles of Operation of Gyro Instruments /6

Depending on the number of degrees of rotation gyroscopes are classified as one-frame, two-frame, and three-frame (free) gyroscopes. In addition, a distinction is made between balanced and unbalanced (heavy) gyroscopes. Each type of gyroscope has its own characteristics. It is these characteristics which have permitted wide use of gyroscopes in very many branches of modern engineering.

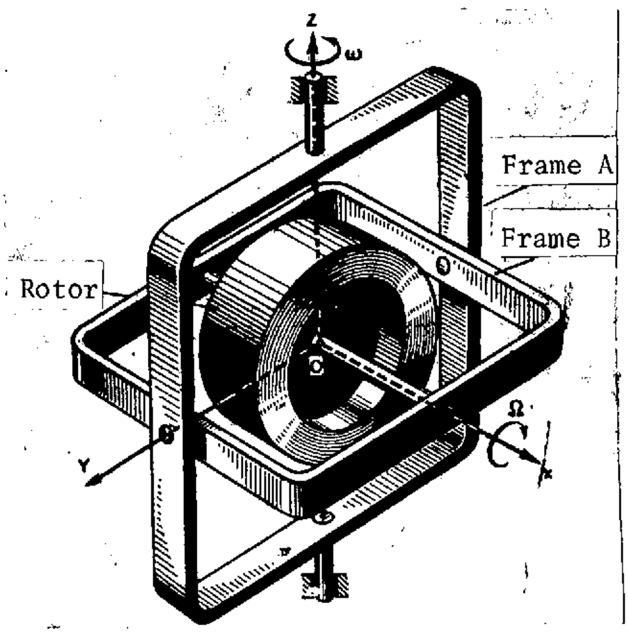

Figure 1. Three-Frame Gyroscope.

Let us consider briefly the principle of operation of a three--frame gyroscope (Figure 1). The rotor, on bearings, is mounted inside frame B and rotates at high speed about axis OX. Frame B can rotate freely about axis OY in external frame A. The latter in turn is free to rotate about axis OZ.

A gyroscope in a suspension such as this (gimbals) consequently has three degrees of freedom.

The OX axis is called the axis of free rotation of the gyroscope. When the rotor rotates simultaneously relative to the axis of free rotation at angular velocity Ω and relative to /7 the OZ axis at angular velocity ω (Figure 2), each elementary particle of the rotor (for example, a_1 and a_2) participates as it were in two movements. In this case these particles of the rotor are subjected to the action of Coriolis acceleration, vector $\overline{\omega}_c$ of which is perpendicular to the plane of the rotor. The force of inertia $\overline{F}_i$, which counteracts the forced rotation, equals the product of the elementary mass of the rotor by the Coriolis acceleration, i.e.,

$$\overline{F}_i = m \cdot \overline{\omega}_c .$$

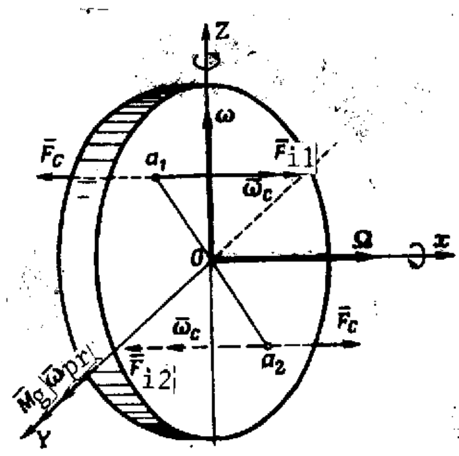

Figure 2. Diagram of Forces and Moments Acting on Gyroscope Rotor.

The force of inertia of the rotor (for points a_1 and a_2 it is force couple F_{i1} and F_{i2}) causes moment M_g of rotation of the rotor about axis OY. Virtually no rotation relative to axis OZ occurs in this case.

Moment M_g is termed the gyroscopic moment. It rotates the rotor at angular velocity $\overline{\omega}_{pr}$ about axis OY. This motion is termed the precessional motion or precession of the gyroscope.

As has already been pointed out, the three-frame gyroscope possesses three degrees of freedom, so that there can be no rotation about axis OZ. For this reason the axis of the gyroscope rotor is stationary in space.

As an example let us consider the principle of angular stabilization of a missile relative to its center of mass by use of an inertial three-frame gyroscope (Figure 3).

Through angle ψ gyroscope G assigns the programmed direction of longitudinal axis OX of the missile. When the longitudinal axis of the missile is deflected by angle $\Delta\psi$ from the programmed direction, this angle is measured by means of the gyroscope and a special sensor sends to an amplifier converter a voltage proportional to angle $\Delta\psi$. The polarity and phase of the voltage depend on the direction and amount of deflection of the longitudinal axis of the missile from the programmed direction. After it has been amplified and converted in the amplifier-converter, signal CY enters the rotor control drive, which eliminates the deflection of the missile.

All existing gyroscopes, and especially inertial ones, cannot keep the axis of natural rotation stationary for a sufficient period of time. For a number of reasons the frames of the gyroscope move spontaneously. As a result there are certain errors in the angles, angular velocities, and so forth measured by the gyroscopes. The errors of inertial gyroscopic instruments and systems are caused basically by the imbalance of individual elements, the inertia of the frames, friction in the universal joint supports, and other factors.

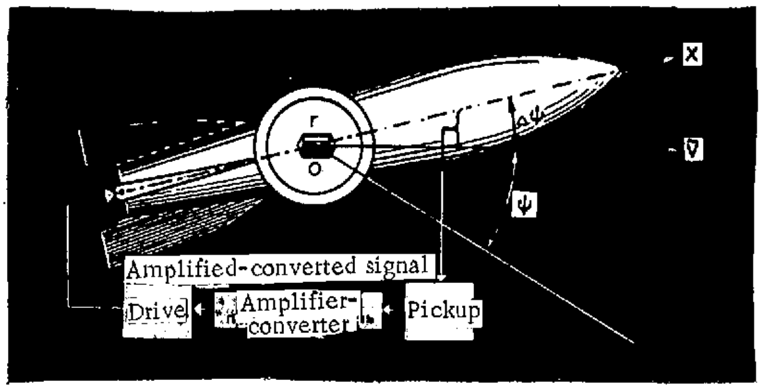

Figure 3. Illustrative of the Principle of Angular Missile Stabilization.

The magnitude of these deflections (errors) is also determined by effective technology of manufacture of individual parts and units.

Electromechanical gyroscopes are the simplest in design and generally are small in size. However, they are characterized by considerable errors because of the deficiencies noted, for which reason it is difficult to solve the number of problems in aircraft navigation, space navigation, and so forth.

Costly research has been conducted abroad for the purpose of reducing the errors of electromechanical gyroscopes, and definite results have been obtained (Table 1). However, the gyroscopes listed in Table 1, although characterized by relatively little drift, can solve control problems in marine, air, and space navigation only in approximation, with considerable errors. /9

The difficulties in reducing the drift of electromechanical gyroscopes and improving their technical characteristics have led to the development of gyroscopes based on other physical principles of operation. Certain technical characteristics of the most recent foreign gyroscopes are presented in Table 2. Their technical characteristics and prospects for use may be evaluated by analysis of Table 2.

According to data published in the foreign press, the most promising of modern gyroscopes in the testing stage is the laser gyroscope. Since in gyroscopes the lasers have resonators in the form of a closed ring, they are often called ring gyroscopes. What properties of laser gyroscopes have made it possible to use them as sensing elements in control and stabilization systems of aircraft, and especially in space navigation systems? To answer this let us turn to Table 3, in which the laser gyroscope is compared with one of the most modern ones now being used for the purposes indicated, the float gyroscope. It must not be thought in this case that the laser gyroscope can in all instances replace the conventional, i.e., electromechanical, gyroscope. The following important conclusions may nevertheless be drawn from Table 3: /12

TABLE 1

Name of Navigational System	Manufacturer	Year of Production	Country	Aircraft	Type of Gyroscope	Gyroscope Drift, degrees/hr	Accuracy of Navigational System,* km/hr
SYG-1000	Sperry	1961	U.S.A.	—	Float	0.01	7.2
SYG-10	Sperry	1965	U.S.A.	Boeing-707	Integrating float	0.02-0.03	Around 5.5
SP-500	Ferranti	1965	England, France	Orbital	Same	Around 0.01	2-3

*The accuracy of a navigational system is to be understood as meaning the magnitude of linear error in determining the position of an aircraft (in kilometers) in one hour of operation of the navigational device.

TABLE 2

Name of Gyroscope	Type of Suspension	State of Completion	Prospects	Basic Characteristics: Kinetic Moment Carrier (Rotor)	Basic Characteristics: Drift Value or Sensitivity
Electro-mechanical	Rotorace bearings	Serial production	Poor	Usually bronze	0.1-0.4 degrees/hr
Float	Combination mechanical and hydro-static	Same	Same	Rotor, bronze, beryl-lium, etc.	0.01-0.03 degrees/hr
With electro-static suspension	Electrostatic	Being developed	Good	Hollow sphere, beryl-lium	10^{-4} - 10^{-5} degrees/hr
Cryogenic	Electro-magnetic	Same	Same	Hollow sphere, titanium and niobium	Drift determined by sensitivity thres-hold of final amplification devices
Hydrodynamic	Bearings	Same	Same	Liquid of high specific gravity	0.01 degrees/hr
Magneto-hydraulic	Mechanical	Has been developed	Same	Liquid, usually mercury	Drift inversely proportional to dimensions
Corpuscular	No suspension	In research stage	Good	Particles of helium and other inert gases	Drift 10^{-4} - 10^{-6} degrees/hr
Gyrotron	No rotating parts	Being developed	Good when improved	Elastic inertial masses	
Laser	Same	Experimental models	Good	None	No drift; sensitivity up to 0.01 degrees/hr

TABLE 2 (CONTINUED)

Name of Gyroscope	Type of Suspension	State of Completion	Prospects	Basic Characteristics	
				Kinetic Moment Carrier (Rotor)	Drift Value or Sensitivity
Electrovacuum	Suspension under weightlessness conditions	In research stage	Good for artificial Earth satellites	Spherical rotor	0.01"/year
Gyroscope operation of which is based on eddy principle	No suspension	Same	Good	Liquid or gas	
Helitron	Same	Same	Same	Plasma	
Josephson ring	No rotating parts	Same	Same	Electron flux	10^{-4} - 10^{-5}
Nonresonant ring, using radiowaves	Same	In production	Poor	None	0.01-0.001 degrees/hr

TABLE 3

Name of Gyroscope	Amount of Drift	Readiness for Operation	Minimum Angular Velocity of Rotation	Sensitivity to Linear Acceleration	Minimum Turning Angle
Float	0.01 degrees/hr	In 20-30 min	Up to 0.001 degrees/hr	Sensitive	Up to 1.5'
Laser	Up to 0.2"/hr	In a few milliseconds	0.1 degrees/ /hr	Not sensitive	Up to 1"

1. The laser gyroscope can operate under high overload conditions. There are in its design no rotating parts the presence of which causes the occurrence of mass imbalance. Hence, great acceleration does not have as great an effect on gyroscope operation.

2. The gyroscopes used in the guidance systems of missiles and aircraft possessing high-speed characteristics must measure angular velocities over a wide range. Modern laser gyroscopes permit measurement of angular velocities of up to 12,000 degrees/hr and above. Other laser gyroscopes can measure angular velocities of 0.001-0.002 degrees/sec.

3. Instantaneous readiness for use is particularly important for aircraft. Until recently gyroscopic instruments were among the aircraft devices /13
requiring considerable time for preparation. For example, float gyroscopes require no less than 20-30 minutes for preparation. Laser gyroscopes are ready for operation immediately after being switched on. This is an advantageous difference between them and the majority of other gyroscopes.

4. The laser gyroscope usually consumes only a few watts of electric power, being the most economical one as regards power consumption.

5. Digital computers are generally used in foreign navigational systems. The laser gyroscope emits an output signal in the form of a digital code; this makes it easy to combine this laser with the navigational device. In addition, because of its properties the laser gyroscope may be used in stageless aviation navigational systems, when the gyroscopic sensing elements are secured rigidly aboard the aircraft.

6. The absence of moving parts renders the laser gyroscope in theory more dependable than the electromechanical one.

All the advantages indicated, and other ones, create broad prospects for use of the laser gyroscope.

1.2. Physical Principles of Laser Operation

Optical quantum generators (lasers) is the name given to devices in which use is made of the phenomenon of forced emission of radiation for the generation of coherent electromagnetic vibrations in the optical range of the electromagnetic wave spectrum.

The phenomenon of forced (stimulated, induced) radiation was first used for the amplification and generation of electromagnetic vibrations in the UHF range, in the microwave region (0.34-10 mm). Devices for amplification and generation of electromagnetic vibrations in this range have received the name of "masers", from the first letters of the words "microwave amplification by stimulated emission of radiation".

Devices operating in the optical wave range, which made their appearance later, i.e., optical quantum generators and amplifiers, received the name of optical masers or lasers. The term "laser" was formed by replacing the letter "m" in the word "maser" by the letter "l" (from the word light) and denotes light amplification by stimulated emission. The term "light" here designates radiation not only in the visible (0.38-0.77 μ), but also in the ultraviolet (0.01-0.38 μ) and infrared (0.77-340 μ) regions of the electromagnetic vibrations spectrum. /14

The terms chosen are not really the best ones, but they have come to be widely used and there obviously is no point in introducing new ones.

Quantum electronics, which explained the principle of laser operation, came into being in 1954-1955. The theoretical substantiation and creation of optical quantum generators may be ranked with the greatest of scientific and technical achievements. The development of quantum electronics is indissolubly linked to the names of the Soviet scientists N. G. Basov, A. M. Prokhorov, A. L. Mikaelyan, and others. In 1955, N. G. Basov and A. M. Prokhorov were awarded the Lenin Prize for discovery of a new principle of generation and amplification. In 1964, N. G. Basov, A. M. Prokhorov, and an American scientist, Ch. Townes, were awarded the Nobell prize for physics for fundamental research in the field of quantum electronics.

Over the last ten years a number of modern quantum mechanical instruments of varying purpose and design: solid-state, gas, liquid, and semiconductor lasers, have been developed on the basis of the first ruby lasers (1960-1961).

A great amount of interest is being displayed in lasers. In the U.S.A. alone, several hundred firms are engaged in a search for new materials for lasers, in improving the characteristics of the existing devices, and in studying their properties.

Lasers are used for welding metals, cutting diamonds and making tiny openings in them, for measurement of angles, distances, velocities, in surgery, in scientific research, in military applications, and so forth.

Lasers are radically new sources of optical radiation in which energy of any kind, including the energy of radiation of an ordinary source of light, /15 may be the primary energy utilized. The primary energy transfers certain atoms of a very specific kind from the basic energy level to a higher one. As a result laser radiation is characterized by high monochromaticity, coherence, directivity, and high power density. In addition, laser radiation is polarized.

The concept "coherence" designates the continuity or coordination between phases of vibrations at different points in space at the same instant in time, or between phases of vibrations at the same point at different moments in time. The time coherence properties of laser radiation is used the most widely in the following cases:

- for the transmission of information on optical frequencies;

- in experiments of all kinds associated with interference;

- for the performance of optical heterodyning in the reception of coherent optical signals;

- in frequency and time standards.

The coherence of electromagnetic vibrations makes it possible to obtain a highly directive light beam of extremely small transverse dimensions.

Since the radiation is coherent, the wave front is generally flat or part of a sphere of great radius, i.e., the laser may be regarded as a source of almost parallel rays of very small divergence. This divergence is determined by the diffraction at the exit aperture. The directivity of laser radiation is achieved not as a result of devices of some kind as in ordinary sources, but owing to the nature of the radiation itself. The laser can nevertheless not be used to create an absolutely parallel beam, because the coherent waves will be diffracted at the exit aperture.

The high directivity is the reason for the following advantages of lasers over conventional sources of electromagnetic radiation:

a) extremely small energy losses associated with beam divergence and with increase in distance;

b) high angular resolution;

c) the possibility of spatial filtration in signal reception, which is /16 accomplished by means of space filters.

Highly directive radiation may be used:

- to transmit information over great distances;

- to transmit energy over great distances;

- in measurement of angles and distances;

- in beam guidance systems, etc.

Radiation densities exceeding the density of radiation of the Sun by several orders of magnitude have now been achieved experimentally by means of lasers. As the result of the enormous density of radiation, any substance is instantly evaporated at the point on which the beam is focused. In addition, the light pressure reaching millions of atmospheres develops in the substance.

Principle of laser operation. Let us consider certain theoretical premises making it possible to understand why the laser generator works. The principle of laser operation is associated with the optical properties of a special so-called inverse medium. As we know, the particles of any medium may be in various states, which are characterized by the structure of the electron cloud (electron states) or by the nature of the relative motion of the ions in the molecule (vibrational and rotational states). The possible stationary states form a discrete sequence which determines the optical properties of the medium.

We know that the atoms and ions of matter are capable of absorbing energy when they are irradiated by quanta of light (photons). At the same time, the energy state of the elementary particles of matter change: the atoms and ions are excited when they receive additional energy and migrate to higher energy levels.

Of all the characteristics of a state we are interested primarily in the intrinsic energy of a particle. This energy is made up chiefly of the kinetic and potential energy of the electrons in the electron cloud of the atom or ion. In the molecule there is added to this the kinetic and potential energy of the relative motion and arrangement of the ions making up the molecule.

The energy excitation of atoms and ions may vary in degree. The energy levels of unexcited particles of matter are usually called ground levels. The ground energy levels are the most stable ones. A particle in this state is stabler as regards energy and possesses a smaller reserve of energy. At the ground energy level a particle can only absorb energy. /17

In addition to the ground level, particles of matter may also be at other, higher, energy levels. A particle possessing a high energy level can not only absorb energy, but under certain conditions also emit it in the form of electromagnetic radiation. The transfers as the result of which electromagnetic energy is emitted or absorbed are called optical transfers. The value of the frequency of radiation of elementary particles of a particular substance depends on the energy levels from which and to which these particles have transferred. If the energy levels of particles of matter change by a definite amount, then the frequency of radiation will also be rigidly defined. But even in this case the radiation may be either chaotic (spontaneous) or ordered (induced), caused by some agent or other.

In the case of spontaneous radiation the energy is emitted in the form of incoherent vibrations. This means that the atoms and ions emit photons spontaneously at different points in time. In this case the energy is emitted mostly within a wide range of frequencies.

The transfer of particles from a higher to a lower energy level under the influence of external factors (external electromagnetic field) is termed induced transfer. In a transfer such as this the energy level changes immediately in the case of a large number of atoms and ions, causing induced emission.

Induced emission is simultaneous synchronous emission of many elementary particles of matter: such radiation is coherent and takes place at frequencies occupying a narrow range.

The medium in which transfers of particles from one energy level to another takes place is called an active level. The particles of an active laser substance are excited by means of a special external source of energy, which is called a pumping generator. In order to obtain coherent radiation it is neces- /18 sary to create laser operating conditions in which the transfer of energy from a higher to a lower level proceeds in an orderly manner under the influence of an external agent. These conditions can be created in an active substance, for example, if it is inside a resonator.

The resonator is an extremely important component of a quantum generator. It is a device analogous in purpose to the resonators employed in radio. It has natural resonance frequencies one of which must coincide with the frequency of laser emission. Resonators are generally made up of two plane, spherical, or parabolic reflectors mounted rigorously parallel to each other. An active (working) substance is placed between them. A resonator such as this is often called an open optical resonator. The reflectors are manufactured with high accuracy (to within hundredths or even thousandths of a micron). The distance between the reflecting surfaces is determined basically by the dimensions of the active medium and may range from tenths of a millimeter (in semiconductor lasers) to several meters (in certain gas lasers).

The active medium may occupy either part of the volume of the resonator cavity or the entire volume (in this case the reflecting surfaces in solid-state and semiconductor lasers are created on the ends of the active substance).

A special place is occupied by the ring resonator, which is made up of reflecting surfaces arranged along the perimeter of a closed outline.

In order to derive useful radiation from the resonator the reflecting surfaces are made to be either partly reflecting or one is fully and the other is partly reflecting. A reflection coefficient of more than 99% on the operating wavelength can be achieved by means of multilayer dielectric coatings.

The basic purpose of the laser resonator is to create conditions such that the induced radiation arising inside it passes through the active medium repeatedly. In other words, the function of the resonator is to perform positive feedback by returning a certain part of the radiation propagated between /19 the reflecting surfaces back into the active medium. If the radiation were to pass through the active medium only once, the power of the emerging radiation would be low, and in addition it would not be propagated in a predominant direction. If the amplification in the medium is sufficient to compensate for the losses, the power of emission will increase until the rate of escape of energy from the resonator reaches saturation, which is determined by the rate of appearance of excited atoms and other parameters as of the system.

The basic types of losses in the resonator are:

- scattering on inhomogeneities of the active medium;

- losses in the resonator reflectors (losses on the ends of the active medium);

- diffraction losses.

The radiation of the laser also increases in power as a result of the fact that it passes repeatedly through the inverse medium, being amplified on each occasion. The phase of the radiation passing through is preserved, so that the radiation is coherent.

The process of amplification is closely related to the directivity of the radiation. The rays propagated at the smallest angle to the longitudinal axis of the resonator pass through the active medium the greatest number of times. It is they which chiefly determine the output power.

Maximum directivity of emission is achieved in the plane-parallel resonator.

Thus the generator performs highly important functions in the laser, determining both the existence of generation itself and the basic properties of the emerging radiation.

1.3. Functional Diagram of a Laser

Let us note what the basic elements are in a laser. They are the active substance, the pumping system, and the resonator.

Their presence is necessary and sufficient for obtaining the laser effect. In practical use of the laser, however, additional devices and systems are usually required, ones which ensure efficiency for the device or are used for control of emission. They include:

- a system of cooling the active substance and elements of the pumping system; /20

- a system of modulating the laser radiation;

- an external optical system;

- a device for monitoring the radiation parameters;

- beam control devices;

- a device for selection of types of vibration.

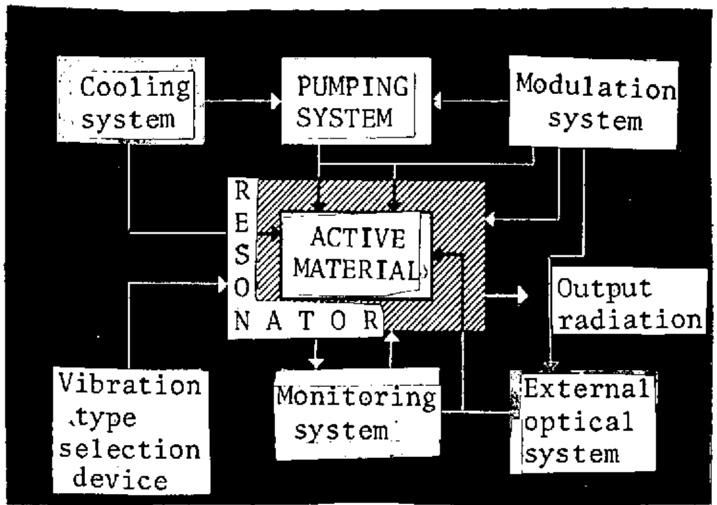

Figure 4. Structural Diagram of Laser.

In each concrete case the presence of one or another of the elements referred to or of all together is not compulsory.

A functional diagram of a laser is given in Figure 4. The basic laser elements are indicated in large print, and systems employed as needed as a function of the concrete purpose of the instrument in ordinary print.

Depending on the state of the active material lasers are classified as solid state (including plastic), gas, liquid, and semiconductor.

Each of these lasers can operate both in the continuous or the pulse mode and in the generation or amplification mode.

In what follows we will be concerned with solid state crystal lasers and above all with gas lasers in our discussion of laser gyroscopes, and so for the sake of simplicity we will consider only lasers of these types. /21

1.4. Crystal Lasers

The first lasers employed in engineering were solid state ruby crystal lasers. At first use was made of the natural ruby; artificially produced ruby crystals are now used. The ruby is aluminum oxide with an admixture of chromium oxide. In structure the ruby is a crystal lattice with three-charge chromium ions embedded in it. The color of a ruby depends on the amount of admixtures. With 0.05-0.07% chromium oxide the color of the ruby is pink, and with 0.5-0.7% it is red. The active material of the ruby laser usually is in the form of a cylindrical rod. The polished ends of the rod are coated with a metal (such as silver) and make up the reflectors of the resonator.

In the ruby laser the crystal lattice is the matrix and the chromium ions the activator. The efficiency of ruby lasers does not exceed 1%. Crystals of small size are used in ruby generation in the continuous mode. A cooling system is generally used in this case.

In the general case the optical pumping system contains a pumping lamp emitting a radiant flux and optical light equipment which concentrates the pumped flux on the active material.

For the purpose of optical pumping use is usually made of special gas discharge lamps 1 filled with xenon, which wind around the rod of active material in the form of a spiral (Figure 5a). To bring about considerable increase in the pumping efficiency use is made of electric reflectors 3 along the focal lines of which the active material and the gas discharge lamps are arranged (Figure 5b). There are also other methods of creating a light pumping flux.

When the ruby rod is illuminated by the bright light of the pumping generator, the chromium ions are excited and migrate from the ground level to a higher energy level. The greatest effect is achieved when the ruby is irradiated with ultraviolet rays and the light rays adjoining them ranging in color from green to violet. The ions migrate from the higher level to the ground level either directly (in which case they emit light energy of a wavelength of 560 nm) or through intermediate levels. The radiation from the upper intermediate level has a wavelength of 693 nm and from the lower level of 694.3 nm. /22

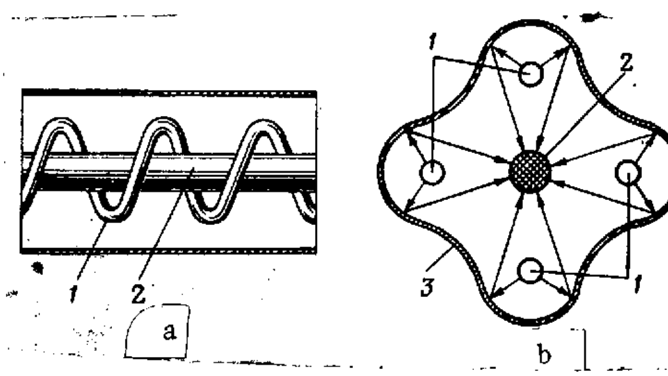

Figure 5. Diagram and Types of Optical Pumping Devices: a, Side view; b, Cross-section.

By proper selection of the resonator dimensions it is possible to create conditions such that vibrations of a wavelength, for example, of 694.3 nm will be amplified. The vibrations of all other wavelengths are incoherent and damp rapidly.

It is necessary to bear in mind the probability of migration of excited chromium ions from a higher level to intermediate ones is greater than that of migration to the ground level. The ions migrate to the intermediate level without emitting energy (this energy is transferred to the crystal lattice of the ruby).

In addition, experiments have shown that the chromium ions retain energy corresponding to the intermediate levels for a fairly long period (0.003-0.05 sec), this being much longer than the time during which the ions are present at the higher energy level or levels. Hence there will be very many ions from the intermediate energy levels. If there are not enough of these ions, they will spontaneously migrate the ground level. The radiation in this case is weak and incoherent and is observed at different wavelengths.

If the excitation energy is sufficient the number of ions at the intermediate levels exceeds the critical value and avalanche transition of excited chromium atoms from intermediate levels to the ground level may begin. /23

When the generation conditions are satisfied the laser begins to emit a flux of coherent lightwaves of one length. The intensity of the induced radiation is very great, exceeding the spontaneous radiation by several orders of magnitude.

1.5. Gas Lasers

Chiefly gas lasers are incorporated at the present time in the optical gyroscopes described in unclassified foreign publications. The builders of these gyroscopes believe that gas lasers will be the most promising ones in the next few years as well.

Let us consider in somewhat greater detail the basic features of the gas lasers which have come to be widely used.

One of the first gas lasers was a laser based on a mixture of inert gases, helium and neon. The mechanism of excitation of a helium-neon laser is based on the interaction of the atoms of these gases, which have similar energy levels. Excitation of the atoms occurs both as the result of collisions between them and electrons and as a result of collisions among the atoms themselves.

Two glow discharge modifications are used for the excitation (pumping) of gas lasers: direct-current discharge and high-frequency glow discharge. In the direct-current discharge a current which does not vary in time passes through the plasma. The electrodes in this case differ in construction and are located inside a tube. Direct voltage (usually 1-2 kV per meter of discharge gap) from a high-voltage rectifier is supplied to the electrodes.

In the case of high-frequency glow discharge a high-frequency (10-50 MHz) alternating current flows through the plasma. The gas laser is pumped by a special high-frequency unit which may include a multivibrator with powerful tubes. A continuous arc discharge arises in the laser under the influence of the pumping voltage.

The necessity of equalizing the energy levels of these gases must be regarded as one of the shortcomings of the helium-neon laser. A conventional diagram of a helium-neon laser is presented in Figure 6. /24

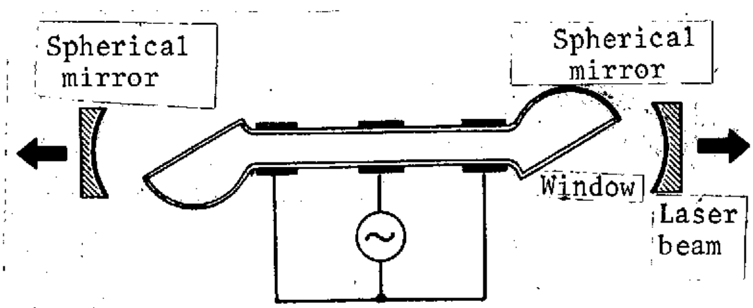

Figure 6. Diagram of Gas Laser.

Gas lasers have been developed the operation of which is based on dissociative transfer of excitation. In such instruments use is made of a mixture of inert gas with a gas possessing a diatomic molecular structure. On collision the excited atom of the inert gas separates the molecule of the diatomic gas into two individual atoms. One of the atoms is then excited to a higher energy level, this leading to emission, while the other absorbs the remaining energy. This eliminates the need for equalizing the energy levels of the two gases entailed by the helium-neon laser. Various combinations of inert and diatomic gases may be used as the active medium in the lasers in question.

Gas lasers have been developed in which the active material is represented by a single inert gas. In a laser such as this certain atoms are ionized as the result of the continuous arc discharge (pumping), and free electrons appear which excite the other atoms of the gas and "raise" them to a higher energy level. Then the electrons pass from the higher energy level to a lower one and in doing so cause coherent radiation.

The gas lasers possess advantages over other lasers, and in particular over the solid state ones. Not the following aspects are essential for laser gyroscopes. Gas lasers possess a high degree of coherence. The generation line of a gas laser is narrower than that of the solid state ones, reaching only a few Hertz. The gaseous medium has a higher optical homogeneity, and for this reason /25 the smallest angle of light beam divergence can be obtained in gas lasers. It is relatively simple to achieve a beam divergence of as little as 1'. In gas lasers having plane mirrors, with no additional collimating devices.

1.6. Methods of Laser Radiation Reception

The luminesce flux emitted by a laser cannot in the majority of cases be used directly as the control signal of a laser gyroscope. For this reason it is necessary first to convert the light signal into an electrical one and then separate the information to be transmitted. For this purpose use is made of laser radiation detectors, which are also often called photodetectors, which convert the energy of laser radiation into an electric signal. They are also used in laser gyroscopes for indication of radiation or separation of the differential frequency of two light beams. Photodetectors may be divided into two groups, thermal and photoelectronic (or quantum and photon).

Thermal photodetectors react to increase in the temperature of a sensitive layer caused by absorbed radiation. A thermoelectromotive force arises or the resistance of the photodetector changes as the result of the heating of the sensitive layer. Thermal photodetectors have one great disadvantage. They are inertial devices and require thermal balance on each measurement, as the result of which their frequency passband is very limited, and in practice they are rarely used in optical gyroscopes.

Quantum photodetectors convert the energy of laser radiation directly into electric energy by use of the photoelectric effect (photoeffect). They react directly to the quanta of radiation. However, not all the quanta participate in formation of a useful signal. As in thermal receivers, part of them are converted into thermal energy and are not recorded. Quantum photodetectors are characterized by selectivity toward radiation of different wavelengths. They also react to variation in the intensity of the luminesce flux, and this in turn modifies the electric conductivity of the sensitive layer or the value of the photoelectromotive force.

Since in quantum photodetectors the photoflux is proportional to the intensity of the optical radiation, they are all quadratic detectors (nonlinear elements). This permits their use as frequency and phase detectors. /26

The photoeffect is manifested in two forms, external and internal. In the external photoeffect the luminesce flux energy absorbed by the sensitive layer is imparted to the electrons of the material. Part of them overcome the forces inside the material restraining them and create a flux of free electrons (photoflux).

In the case of the internal photoeffect internal excitation of the crystal lattice of the semiconductor material occurs as a result of the luminesce flux, so that the electrons are transferred from the bound state to free ones without emerging to the outside. In this case the energy of the photoflux is not sufficient for formation of electron emission but is enough for the appearance of a free electron and a free hole.

Photoelements, electrostatic photoelectron multipliers, and so forth may be used in optical gyroscopes as photodetectors with an external photoeffect. Among the photodetectors with an internal photoeffect use may be made of semiconductor photodiodes and phototriodes.

Before we consider the basic types of photodetectors, let us explain the meaning of certain basic parameters on the basis of which they may be compared. The spectral and integral sensitivity, the threshold sensitivity, the quantum efficiency, and the frequency characteristic may be considered to be such parameters.

The spectral sensitivity S_λ is the relationship of the photodetector sensitivity to the wavelength of a monochromatic luminesce flux. The spectral sensitivity of a photodetector depends on its temperature. When a photodetector is cooled the spectral characteristic maximum is displaced in the direction of the longer wavelengths.

The integral sensitivity S represents the ratio of the photoflux in the photodetector circuit to the intensity of the luminesce flux and is expressed in microamperes per watt (μa/wt) or (for the visible portion of the spectrum) in microamperes per lumen (μa/lm). The integral sensitivity may also be defined /27
as the ratio of the signal voltage at the photodetector output to the intensity of the luminesce flux caused by this signal. In this case (for photodetectors with an internal photoeffect) the sensitivity is expressed in volts per watt (v/wt). The threshold sensitivity Φ_{thr} is the minimum luminesce flux intensity value which can be recorded by the photodetector. Its value cannot exceed the noise level of the photodetector at which the signal-noise ratio equals unity.

The quantum efficiency η of a photodetector is defined as the average yield of electrons per incident photon. For detectors with the external photoeffect this yield is usually small, falling within the range of $1 \cdot 10^{-5}$-0.2; the latter figure can be achieved only over a narrow frequency range. The quantum efficiency of photodiodes is near unity.

The frequency characteristic expresses the relationship of the photoflux (photoelectromotive force) to the modulation frequency of monochromatic radiation and characterizes the inertia of the photodetector. The inertia of photodetectors is sometimes defined as the value of the time constant in which the photoflux reaches its maximum value from the beginning of irradiation of the photosensitive surface by a constant luminesce flux. It is to be noted that high time parameters of photodetectors represent a necessary but not sufficient condition for their having a wide band.

Now let us consider certain basic types of photodetectors which can be used in laser gyroscopes.

External photoeffect detectors. The parameters of external photoeffect detectors depend on the photoemission characteristics of the materials making up the photocathode. The second electrode in such instruments is the anode, to which a high positive voltage is usually supplied. The photoelectrons emitted under the influence of this voltage rush toward the anode, creating a current in the external circuit. A device such as this is called a photocell.

The modern photocell is usually a glass envelope from which the air is evacuated. The greater part of the interior wall of the envelope is spray /28
coated with metal and represents the photocathode, while the role of anode is performed by a metal ring or plate located in the center of the envelope.

It is to be noted that a current, called a dark current, flows in the circuit of the photocell even when the photocathode is not irradiated by a luminesce flux. The dark current is caused by the thermal emission current of the photocathode and the leakage current between the electrodes. Change in the value of the dark current results in internal photodetector noise.

In order to increase the integral sensitivity of the photocells use is sometimes made of amplification of the primary photocurrent by ionization of an inert gas which fills the photocell envelope (gas filled photocells). A disadvantage of gas filled photocells is represented by their great inertia.

The relatively low sensitivity of vacuum photocells and the high inertia of the gas filled ones restrict the possibility of their use. Use is much more often made of electrostatic photoelectron multipliers, in which the primary photocurrent is amplified by means of the secondary electron emission effect.

An electron emitted by the photocathode is accelerated by voltage U_1 and is directed to electrode D_1, which is termed a dynode. Several new electrons are dislodged from its surface and are accelerated by voltage U_2 and directed to the following dynode D_2; this continues until the last multiplication stage has been reached, from which the electrons reach the anode, which is under positive potential.

Current amplification in the photoelectron multiplier depends on the number of multiplication stages (dynodes) and the secondary emission coefficient δ of each stage, which is defined as the number of secondary electrons per primary electron. This coefficient depends on the voltage between the dynodes, the size and arrangement of the latter, and the composition of the emission material. Usually $\delta = 3\text{-}10$, and the number of stages $n = 9\text{-}14$. The current amplification factor of a photoelectron multiplier is defined as ratio $K = \delta^n$ and usually exceeds 10^6, this corresponding to a power amplification of 120 dB. The time resolution of a photoelectron multiplier may be less than 1 nanosec; the upper limit of the frequency characteristic is usually 100-200 MHz, and in the best models reaches 300 MHz. /29

Internal photoeffect detectors. Photodiodes and phototriodes. The principle of photodiode operation consists in the following. When a photodiode is not illuminated, and inverse voltage is supplied to the p-n junction, there will flow through the junction a small current caused by the minority current carriers, electrons in the p region and holes in the n region of the semiconductor. When the photodiode is illuminated, electron-hole pairs occur on the boundary of the n region. The holes, being the minority carriers in this region, are diffused into the interior and are drawn into the p region as they approach the junction. It is necessary for this purpose that the thickness of the n layer be less than the diffusion length and that the holes reach the p region before they are recombined. Increase in the minority carrier current causes additional drop in the voltage on the load resistance. The additional drop in voltage also represents a useful signal. Photodiodes may operate both in the valve mode (with no external power supply source) and in the photodiode mode, when the power supply voltage (8 to 100 v) is applied in the cutoff direction.

The photocurrent is amplified as well as induced in phototriodes when the latter are irradiated by a luminesce flux. Hence the integral sensitivity of phototriodes is higher than that of the photodiodes, reaching several amperes per lumen.

Photodiodes and phototriodes may be of the point-contact and junction types and are made of germanium, silicon, and indium selenide and arsenide.

2. Principle of Operation of the Laser Gyroscope /30

It was stated earlier that laser gyroscopes possess a number of advantages over the electromechanical ones. These advantages provide broad prospects for practical utilization of laser gyroscopes. For example, the method and form in which output data are taken from gyroscopes is always a matter of very great importance to the designers of control systems.

With the laser gyroscope it is possible to obtain at the output signals which are convenient for control, for example, in the form of a sequence of electric pulses the polarity of which is determined by the direction of rotation of the gyroscope. The number of individual pulses is proportional to the small fixed turning angle increments (for example, one second of arc). The total turning angle of the gyroscope is found on the basis of the total number of pulses.

The accuracy of instrument operation is of even greater importance to designers. The operation of laser gyroscopes is characterized by extremely high accuracy. Since they must register a speed of rotation less than 0.1°/hr because of the purpose for which they are used, it is necessary to measure a difference in optical trajectories with an accuracy of 10^{-5} nm and frequency changes of around 0.1 Hz (at an operating frequency of 10^{-14} - 10^{-15} Hz.

The simplest design of such a device is represented by the usual arrangement with three reflecting mirrors arranged at outline angles in such a way that a closed trajectory (ring) is formed for the light beam.

The laser beam (Figure 7) is created by two quantum generators one of which emits radiation clockwise and the other counter-clockwise.

Two quantum generators are cited in order to simplify the discussion. In practice one optical quantum generator having two or more active elements forming beams moving in opposite directions may be installed in the laser gyroscope.

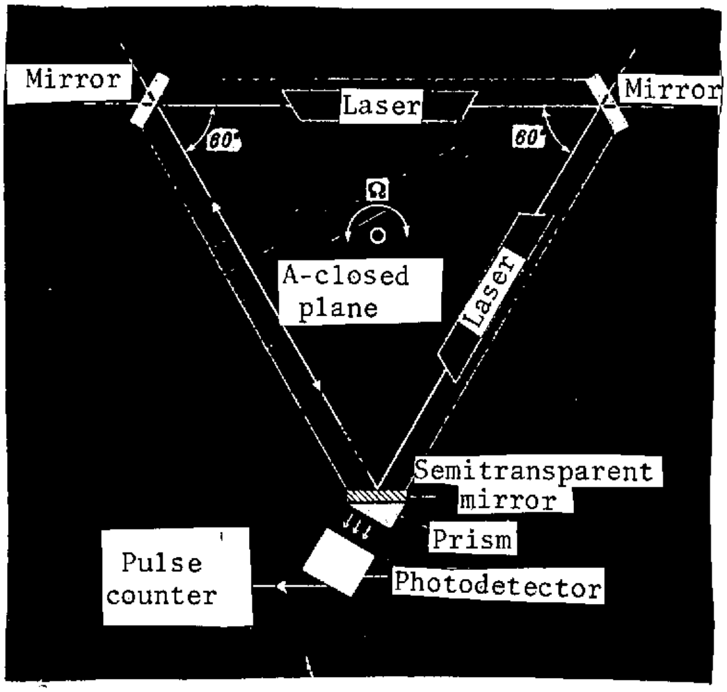

Figure 7. Basic Diagram of the Laser Gyroscope.

The luminesce radiation is attenuated after being reflected from the mirrors and passing from mirror to mirror and, lastly, through the semitransparent mirror and prism. In order to keep the light waves in the system at a level necessary for normal operation it is necessary for the amplification factor of the light rays to be no less than one over the entire path. It is also necessary for the entire number of wavelengths generated by lasers to be confined to the path length of the laser rays, that is, the phase shift of the light vibrations in the resonator cavity must equal zero. In order for this last named condition to be fulfilled the vibrational /31 /32 frequency of the laser must be such that the amplifying medium will yield an amplification factor sufficient for compensation for the losses in the reflecting and other elements of the laser optical circuit. This frequency is established automatically during operation of the laser.

On rotation of the ring resonator in the inertial space the optical paths traversed by the beams moving clockwise and counter-clockwise are not the same. The difference between the optical paths leads in this case to a difference in frequency between the vibrations generated (the Sagnac effect), which determines the speed of rotation of the resonator.

2.1. Principles of Laser Gyroscope Theory

It follows from the general theory of relativity that time is not the same to two observers moving in opposite directions over a closed path in inertial space. Time passes more rapidly for the observer moving in the direction of rotation and slower for the observer moving opposite the direction of rotation.

The laser gyroscope theory is accordingly based on the premise that the path length over the cycle will differ for an observer (photon) moving in the direction of rotation and one moving opposite the direction of rotation.

Time difference Δt for both observers in one revolution depends on speed Ω of rotation of the circuit in space and the area of the circuit A. In this case

$$\Delta t = \frac{\Omega}{c^2} 2A + \frac{\Omega}{c^2} 2A = \frac{4A\Omega}{c^2},$$

where c is the velocity of light;

A is the area of projection of the circuit onto the plane of rotation;

Ω is the angular velocity of rotation (turn) of the gyroscope.

For two bundles of photons moving in opposite directions in the laser gyroscope time difference Δt is proportional to the difference in their optical paths ΔL, since /33

$$\Delta L = c\Delta t + \frac{4A\Omega}{c},$$

where $\Delta L = L_1 - L_2$.

It is to be seen from the formula that the speed of rotation or the area of the circuit must be sufficiently large in order to obtain a sufficient difference in optical paths.

In practice measurement is made not of the difference in optical paths of the moving gyroscope circuit but of the difference in vibrational frequencies Δf of two light beams moving in opposite directions.

This measurement is mostly performed by means of a photodetector at the output of which a signal is obtained which corresponds to the positive or negative phase shift determined by the direction of rotation of the gyroscope.

Vibrational frequencies f_1 and f_2 of the rotating gyroscope are determined by the relations:

$$f_1 = \frac{cq}{2L_1};\ f_2 = \frac{cq}{2L_2},$$

where q is the full number of waves fitting into the distance between mirrors;

$L_1 = p + \frac{2A}{c}\Omega$ is the length of the optical path of the first beam;

$L_2 = p - \frac{2A}{c}\Omega$ is the length of the optical path of the second beam.

The vibrational frequency in the gyroscope at rest is $f_0 = \frac{cq}{2p}$.

With the last named relationships taken into account the relationship between the difference in frequencies and speed of rotation Ω (with Ω = const) will be of the form

$$\Delta f = f_2 - f_1 = \frac{cq}{2L_2} - \frac{cq}{2L_1} = \frac{cq}{2} \cdot \frac{L_1 - L_2}{L_1 L_2}.$$

But since $L_1 - L_2 = \Delta L = \frac{4A\Omega}{c}$,

$$\Delta f = \frac{cq}{2} \cdot \frac{\frac{4A\Omega}{c}}{\left(p + \frac{2A}{c}\Omega\right)\left(p - \frac{2A}{c}\Omega\right)} = \frac{cq}{2} \cdot \frac{\frac{4A\Omega}{c}}{p^2 - \frac{4A^2}{c^2}\Omega^2}.$$

Since the perimeter of the circuit usually is $p \gg \frac{4A^2}{c^2}\Omega^2$, by simplifying /34
the last formula we obtain

$$\Delta f = \frac{cq}{2} \cdot \frac{4A\Omega}{c} \cdot \frac{1}{p^2} = \frac{cq}{2p} \cdot \frac{4A\Omega}{cp} = \frac{f_0}{c} \cdot \frac{4A}{p}\Omega.$$

Designating $\frac{f_0}{c} \cdot \frac{4A}{p} = B = \text{const}$, we obtain

$$\Delta f = B\Omega.$$

Coefficient B, which is called the laser constant, characterizes the sensitivity of the laser gyroscope.

The sensitivity of the laser gyroscope is the higher the larger is the value of B. The value of B is 10^{-5} - 10^{-6} or more for modern laser gyroscopes.

2.2. Certain Experimental Data Obtained in Work with Laser Gyroscopes

Certain experimental data on ring lasers are given in the American literature. In determination of the speed of rotation of the Earth a circuit of an area of 20 m^2 was rotated at its speed of revolution, a difference in optical paths of 10 nm being obtained. These data coincide almost exactly with the calculated data.

A gas laser operating at a frequency of around $3 \cdot 10^{14}$ Hz was used in the experimental gyroscope. The generator frequency was adjusted so as to keep it within limits assuring absence of a phase shift between the vibrations generated and those moving over the circuit over the entire range of variation in the speed of rotation of this circuit.

The amplification of the light beam in the laser, which equaled 1.01-1.05, was produced by means of an electric discharge in a gas consisting of 10 parts helium to one part neon. The gas mixture was under a pressure ranging from 1 to 10 mm Hg.

Data have been published in the foreign literature [5] on testing of a laser gyroscope. The tests were conducted to determine the accuracy characteristics of a ring laser angular velocity sensor and the relationship of these characteristics to the magnetic and gravitational fields.

The sensing element unit consisted of three-ring (triangular) gyroscopes, /35
each side having a length of 12.7 cm.

The unit was in the form of a cylinder 25.4 cm in diameter and 17.8 cm in height. The static and dynamic errors were measured to assess the accuracy of the laser sensor. The stability of the gyroscope parameters was checked on a precision turntable. The static error measurements revealed that the drift of the gyroscope during the first hour of testing equal 0.4°/hr, and decreased substantially over the following four hours. The gyroscope was rotated at constant speeds for the purpose of measurement of the dynamic errors. The dynamic error amounted to 0.01% in the range of small and large angular velocities.

In order to evaluate the influence of the gravitational field on gyroscope accuracy the gyroscope was mounted on a precision optical homing device. The drift of the gyroscope was determined by rotating it about the axis of sensitivity. The tests were conducted with the gyroscope in different positions in the gravitational field of the Earth. Analogous tests were also conducted to evaluate the influence of the magnetic field. In this case the gyroscope was placed on a nonmagnetic base inside a Helmholtz coil.

The tests showed that the gravitational field of the Earth and g-forces have virtually no effect on the accuracy of the laser gyroscope, and that an error in laser gyroscope measurement of angular velocity of 0.03°/hr corresponds to the value of the magnetic field of the Earth.

2.3. System of Reading Laser Gyroscope Data

Several different methods may be employed to read the angular velocity of rotation of a laser gyroscope. For example, the angular velocity may be determined by measuring the frequency difference of two beams.

The method of determining the phase shift of incoming signals is a more accurate method in the case of small angular velocities of gyroscope rotation.

One of the possible systems of determining the phase deviation of light vibrations to read data from a laser gyroscope is illustrated in Figure 8, which shows a dielectric mirror, one of the reflecting mirrors of the circuit, and a beam splitter prism. The mirror does not fully reflect the beams striking it. A certain portion of them (approximately 1%) pass through it and are separated, /36 being refracted by the prism. The beams propagated clockwise in the circuit (first beam) and counter-clockwise (second beam) pass through the prism to form interference bands on scree AA. This is possible because the angle at the apex of the prism does not equal 90° exactly, and angle Θ formed after refraction of the first and second beams does not equal zero.

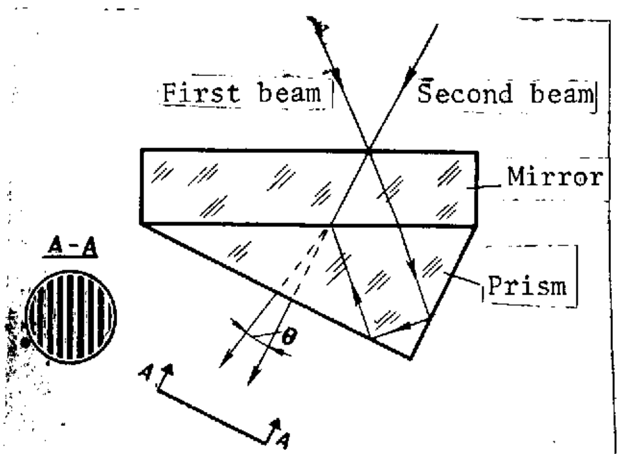

Figure 8. Diagram of Beam Splitting.

If the phase difference between the light vibrations of these beams remains constant, the bands will be stationary.

On change in the phase difference the interference bands shift to the left or to the right as a function of the direction of rotation of the circuit. Displacement by one step between bands corresponds to a change in phase of 2π radians.

The direction and rate of change in phase are determined by means of two photoelectric detectors shifted 1/4 step between bands relative to each other. Thus the output signals of the detectors are shifted 90° relative to each other. By connecting the detectors to an oscillograph one can see the output signal of a gyroscope on the oscillograph screen in the form of a Lissajou figure.

When the gyroscope is rotated clockwise the interference pattern is displaced, this forcing the image on the oscillograph screen to move in a circle /37 in a definite direction.

The direction of movement of the circle on the screen also changes on change in the direction of rotation of the gyroscope.

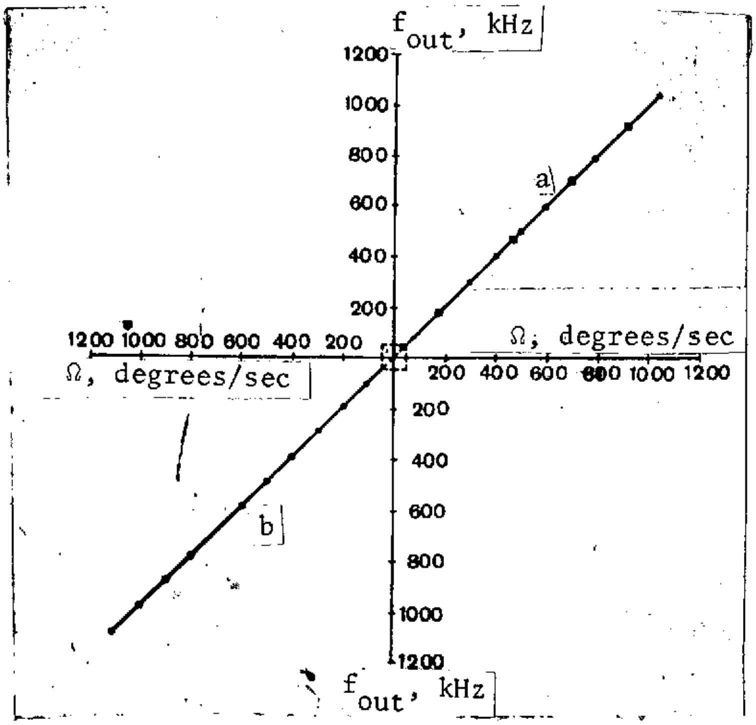

Figure 9. Beat Frequency of Output Signal Versus Speed of Rotation of High-Speed Gyroscope.

The output signals of the detectors are calculated by means of binary counters, each reading corresponding to a phase change of 2π radians. At a speed of gyroscope rotation equaling $1°$/hr a rate of phase change of 2π radians per second can be obtained.

The output pulse frequency is plotted against the speed of rotation of a laser gyroscope in Figure 9, in which a denotes clockwise rotation and b counter--clockwise rotation. The zone of insensitivity is outlined by a dotted line.

Let us now consider one of the first models of a laser gyroscope produced by Sperry Rand Corporation, which is designed for use in investigation of the /38
possibility of using these gyroscopes in navigational instruments.

Four gas (He-Ne) continuously operating lasers placed on the sides of a square to form a closed resonator (ring) were used in the gyroscope (Figure 10). Unlike the ordinary laser, in which only one end of the tube emits, in this gyroscope all four lasers emitted in two directions. A mirror arranged at an angle of 45° to the axis of the lasers was mounted in each of the four corners of the laser ring, so that the light emitted by one laser was reflected toward the adjacent one. Thus the energy emitted by each laser circulated around the ring. But since each laser emits energy from both ends of the tube, there were /39
produced in the gyroscope two light beams moving in opposite directions around the circle. As has already been pointed out, a frequency difference arises between beams when a gyroscope is rotated about the axis.

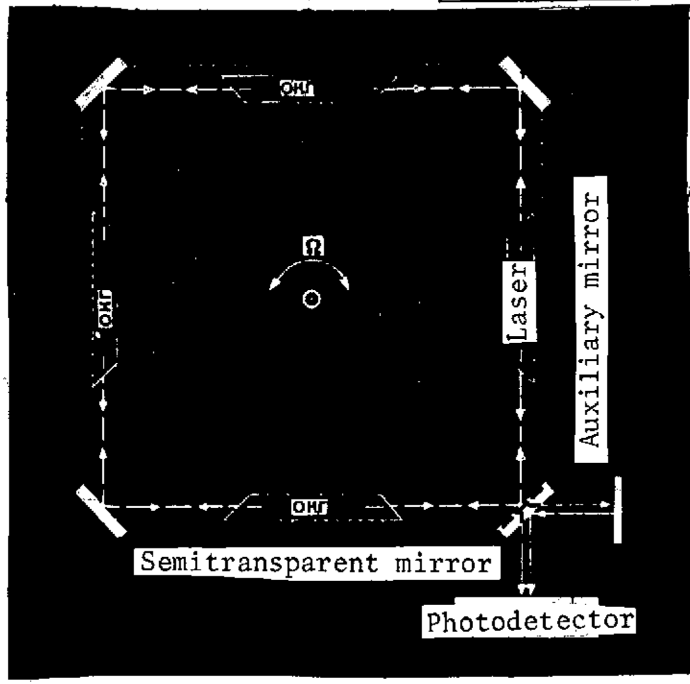

Figure 10. Diagram of Model Optical Gyroscope.

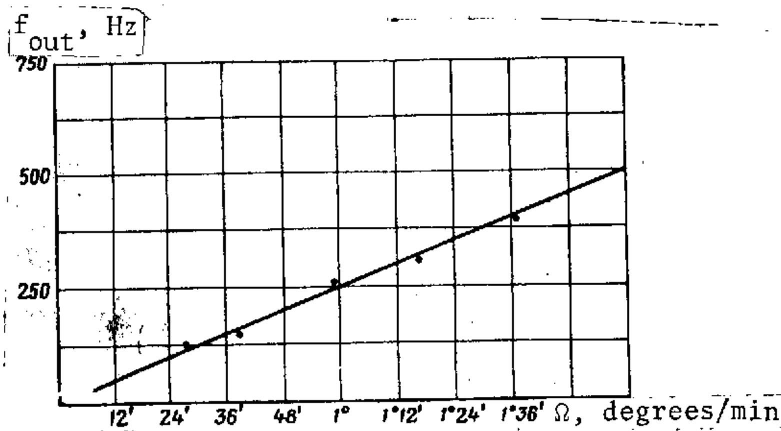

Figure 11. Output Signal Beat Frequency Versus Rotational Speed of Platform of Gyroscope Measuring Small Angular Velocities.

The resulting frequency difference was measured optically by the beam splitting method already discussed. For this purpose one of the corner mirrors was coated with a thin layer of silver so that the necessary energy of two opposite light beams passed through the mirror and the remainder was reflected and continued to circulate around the circle.

An auxiliary plane mirror was used to reflect one of the beams backed to the corner mirror. For this reason both beams emerged from the laser ring in the same direction and struck the photodetector. As a result of the mixing of these beams frequency beats occurred which were directly proportional to the angular velocity of rotation of the laser ring and the optical length of each arm of the frame, and inversely proportional to the wavelength of the radiation of the lasers.

The optical length of an arm was approximately 1 m and the wavelength of the radiation of the He-Ne lasers equaled 1.153 μ. A signal of a slip frequency of 250 Hz per degree of angular rotation per minute was taken from the photodetector output (Figure 11).
In testing of the instrument /40
at a speed of rotation of 2°/min (the minimum turning speed) an output signal frequency of 500 Hz was obtained, and 150 kHz at 600°/min (the maximum turning speed).

Let us now consider another type of laser gyroscope which has also been put to practical use.

2.4. One-Piece Laser Gyroscope

The brittle, easily deformed tubes of gas lasers and the individually mounted mirrors in the first experimental instruments resulted in unstable instrument operation. A sufficiently massive frame was needed to assure rigidity of design.

To provide compactness and durability the laser gyroscope manufactured by Honeywell was placed in a block made of a lump of high-quality quartz. The openings and resonators in the block for the light guides, anodes, cathodes, and filled channels were obtained by machining. The mirrors (of which there are three in the instrument; see Figure 12) were applied to the surface at the corners of the block by the molecular adhesion method in order to provide sufficient rigidity for the system. A beam splitting separating prism was connected to the output mirror; after passing through it the beams struck a photodetector. Before the molecular adhesion the contact surfaces of the quartz and mirrors are made as flat as possible and are carefully polished. The interior cavities are filled with a helium-neon mixture under a pressure of around 5 mm Hg.

A pumping voltage of around 1 kV is supplied between the anode and the cathode to create the laser effect. The dimension tolerances of the block had to be small enough to guarantee occurrence of the laser effect. The specialists of this firm believe that they have successfully overcome a number of difficulties relating to machining of the block and have reached a level of technology such that the instruments can be manufactured by industrial enterprises after a certain amount of development. The relative simplicity of design of the quartz block permits the hope that laser gyroscopes will be cheaper than the conventional ones. It is also stated that this laser gyroscope possesses a number of essential advantages over other types of optical gyroscopes; for example:

- it possesses greater rigidity, since the brittle discharge tubes of the gas laser are not used in it; /41

- it is fairly simple to adjust, since the number of elements is smaller, and losses of light due to scattering are reduced; in addition, since there is an odd number of mirrors, they are automatically adjusted in the horizontal plane;

- it is small in size, since no cumbersome light guide is required.

The first laser gyroscope with a ring resonator had a light guide length of 390 cm and an area of 9,000 cm^2.

The total light guide length of the quartz block is no greater than 32 cm. The block takes up an area of only 90 cm^2. The gyroscope weighs around 2 kg and can measure rotational speeds of the order of 0.1°/sec.

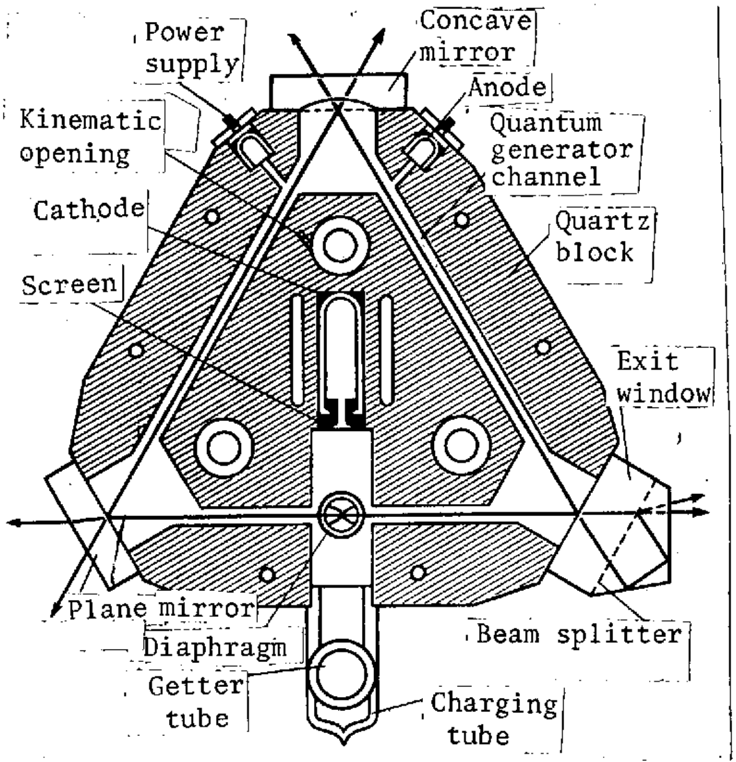

Figure 12. Design of Laser Gyroscope.

This gyroscope is uniaxial, i.e., it can measure angular deflections in one plane only. Hence the idea quite naturally arose of developing a triaxial spherical laser gyroscope. /42

The firm of Honeywell produced such a gyroscope. It consists of three uniaxial gyroscopes each of which measures the speed of rotation about one orthogonal axis. The outer diameter of the gyroscope is around 13 cm. According to the manufacturer, the instrument is capable of measuring small rotational speeds (less than 0.1°/sec).

The gyroscope may be fastened on the gimbals of a tracking system and measure the angular speed of rotation of tracking devices, such as those of a missile. This instrument is proposed for use in space navigation.

Let us now consider in brief the basic difficulties facing the developers of laser gyroscopes, who are striving to achieve maximum measurement accuracy from gyroscopes along with minimal size.

2.5. Sources of Errors and Restrictions Affecting the Accuracy of Measurement and Dimensions of Laser Gyroscopes.

As is shown in foreign publications, the basic sources of errors restricting the accuracy of measurement of the angular speed of rotation of laser gyroscopes are:

- the multiplicity of radiation modes;

- the fluctuation of the phase and frequency luminesce radiation;

- forcing of oscillations;

- the "zero drift" of the gyroscope.

Let us consider in greater detail these factors upsetting stability.

Multiplicity of modes of gas laser radiation. Several different vibrations (modes) of different frequencies may be excited in the ring laser. On rotation of the gyroscope at angular velocity Ω the multiple load generation conditions result in splitting of each mode into two frequencies. The beat frequency differences of adjacent modes differ somewhat from each other in this case, this making it difficult to distinguish the differential frequency signal clearly and to evaluate the angular speed of rotation. For this reason, in actual laser gyroscope designs an effort is made to assure generation conditions approximating single mode generation. One of the means of suppressing undesirable vibrational modes is adjustment of the amplification of the laser /43 active medium in such a way that the amplification will not compensate the active resonator losses in all the modes except one. In this case generation occurs at one frequency only.

Fluctuation of radiation phase and frequency. The stability of the phase and frequency of the laser generator is in the last analysis limited by spontaneous emission of photons of the active material.

The phase of the basic radiation may vary by an amount proportional to the total amount of spontaneously emitted photons. Variations have been very substantial in this instance. But since the photon emission phases generally do not coincide, the fluctuations in the magnitude and phase of emission are small. However, this phase shift is random in nature. The dispersion of the basic radiation frequency for gas lasers ranges from 0.001 to 1 Hz. In effect the accuracy of angular velocity measurement is limited to the minimum phase value which can be measured by a photodetector. It is to be expected, however, that as improvement is made in the technology of manufacture of laser gyroscopes and their components the accuracy of measurement of angular positions will approach the limits determined by the fluctuations of generator phase and frequency.

Forcing of oscillations. At high speeds of gyroscope rotation the frequency difference of optical generators is proportional to the speed of rotation. However, as this speed decreases the frequency difference approaches zero more rapidly than does the speed of angular rotation of the gyroscope.

As a result, at low speeds of rotation the errors in measurement of angular velocity become intolerably large, and at the lowest velocities the gyroscope does not register the initial rotation at all (section AA, Figure 14). So-called forcing of oscillations of one generator by another occurs as the result of the mutual influence exerted by the two generators.

Capture of beams propagated in opposite directions is due to their back-scattering, for which reason reduction of this capture zone amounts above all to reduction of this scattering. It is necessary for this purpose:

- to reduce scattering on the gyroscope mirrors to a minimum; /44

- to create as high a vacuum as possible in the channel over which the rays are propagated;

- to reduce to the minimum the influence exerted by the active material plasm of the optical circuit.

In addition, the capture zone is reduced on increase in the perimeter described by the beams and the diameter of their flux, as well as on increase in the wavelength of emission.

Choice of the wavelength of generated vibrations is limited to the values at which it is possible to maintain the generated vibrations in the laser gyroscope. The extreme values of the amplification factor are limited by the scattering of the light beam, which increases greatly on reduction in wavelength.

Hence the scattering caused by the windows, mirrors, and other structural components of the gyroscope cavities is reduced to the minimum. However, the bonds arising on scattering on the molecules of gas in the quantum generator limit the amplification factor of the light circuit to a value at which it is virtually impossible to detect a speed of rotation lower than 1°/hr.

The capture zone for a laser gyroscope having an area of $A = 0.1\ m^2$ is usually 100°/hr, this corresponding to a generator vibrational frequency difference of 100 Hz at a laser wavelength of 632.8 nm (red light).

Zero drift. Yet another source of laser gyroscope errors is represented by zero drift. This error is equivalent to the fixed moment of displacement in the conventional mechanical gyroscope.

The zero displacement is to be ascribed to the occurrence of gas fluxes in the gyroscope cavity. The existence of these fluxes in a gyroscope the quantum generators of which are supplied with direct current is due to collision of the gas molecules with the walls of the gyroscope cavities and by the distributions of the electric charge along the walls and the electric field along the course of the gas discharge.

The nature of distribution of gas fluxes in the laser gyroscope is illustrated in Figure 13, in which 1, 2 are anodes, 3 is the direction of the gas flux, 4 the cathode, and 5 the tube.

The laser beam is concentrated in the central portion of the gyroscope cavity and passes through the gas moving toward the cathode. Gas flows in the /45
opposite direction along the walls of the tube. The displacement of the gas leads to change in the refraction index, which depends on the relative directions of displacement of energy in the laser beam and the gas flux.

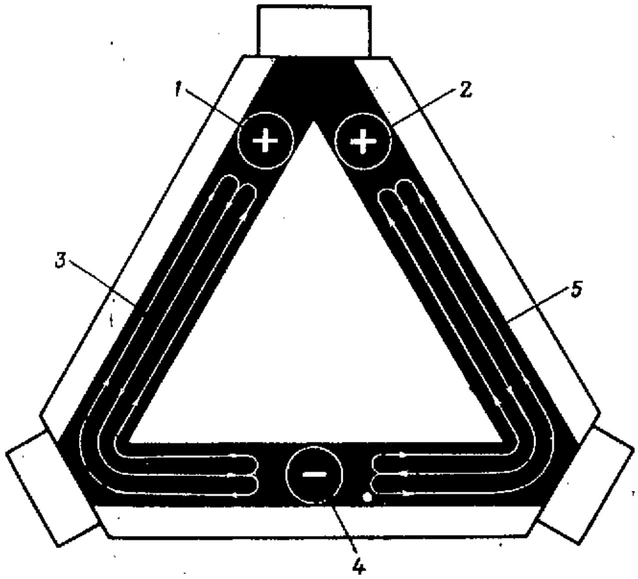

Figure 13. Distribution of Gas Fluxes in the Laser Gyroscope.

Hence the gyroscope cavity will be somewhat longer in one direction than in the other. It is this effect which results in the zero drift of the gyroscope.

The zero drift may be reduced if the gyroscope is made so as to be symmetrical in design with two anodes and one cathode and the anode currents are balanced until a minimum zero drift value is achieved.

In a gyroscope having only one anode the zero shift is usually found to be equivalent to an output speed of rotation of the order of several hundred degrees per hour.

The upper limit of the angular velocities which can be measured by a laser gyroscope is determined by the passband width of the quantum generators, which equals approximately 1 Hz.

Since at a rotational speed of 1°/hr the frequency difference of a laser is 1 Hz, the gyroscope permits measurement of rotational speeds of up to 10^{-8}°/hr. However, since the frequency difference of the laser represents a considerable portion of the passband, this speed may be reduced owing to nonlinearity of the gyroscope characteristic. Experiments conducted abroad indicate that this characteristic is sufficiently linear only up to speed values of $4 \cdot 10^{6}$°/hr. /46

At high rotational speeds rigid requirements are also set for the passband of the photodetector and amplifiers. For example, according to American data, at a rotational speed of 10^{8}°/hr the passband of the measurement channel must be no less than 100 MHz.

2.6. Methods of Increasing the Accuracy of Measurement of Laser Gyroscopes.

The methods of eliminating the influence of the forcing effect are based on imparting to the gyroscope forced rotation (real or apparent) at a known constant speed. This makes it possible in measurement of low rotational speeds to displace the operating characteristics of the gyroscope into the region of higher speeds situated outside the nonsensitivity zone, in which there is no forcing of laser oscillations. In this instance the resultant speed of rotation of the laser gyroscope represents the algebraic sum of the true speed and the speed of displacement.

This displacement can be achieved:

- by rotation of the gyroscope at a precisely known angular velocity;

- by mounting in the optical path special elements having refraction indexes which depend on the direction of movement of the beam (so-called non-reciprocal elements);

- forced movement of the active gaseous medium at a known angular velocity (utilization of the Fresnel-Fizeau drag effect).

Let us consider these methods briefly.

<u>Elimination of the effect of capture by mechanical rotation of the gyroscope</u>. Displacement of the operating point of the characteristic from the nonsensitivity zone may be fixed or periodic. In the case of fixed displacement, which is achieved by rotation of the gyroscope, the signal proportional to the /47
true rotational speed Δf_{tr} of the gyroscope is obtained by subtracting equivalent shift signal Δf_{sh} from the resultant signal Δf_{res}.

As may be seen from Figure 14:

$$\Delta f_{tr} = \Delta f_{res} - \Delta f_{sh}.$$

In the absence of displacement angular velocity Ω_{tr} is in the nonsensitivity zone.

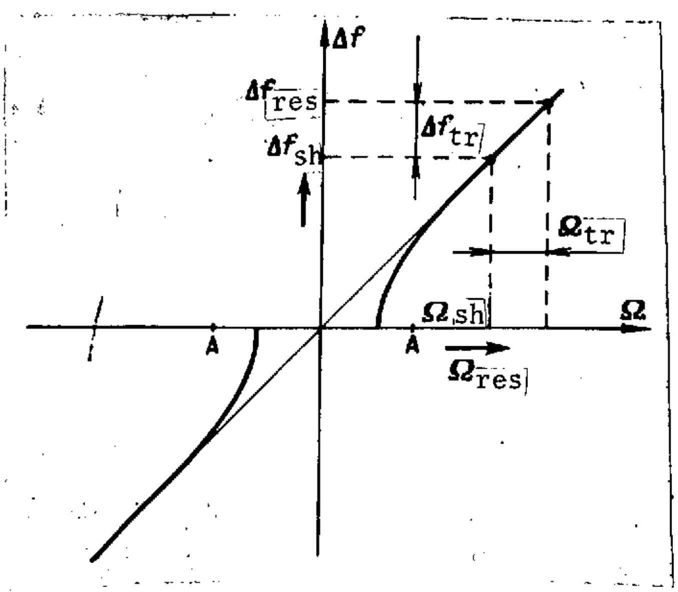

Figure 14. Displacement of Operating Point on Gyroscope Characteristic From Nonsensitivity Zone.

A fundamental disadvantage of fixed displacement is represented by the rigid requirements set for displacement stability. For example, the stability of the angular speeds of displacement must be no less than 10^{-8}°/hr for measurement of angular velocities of the order of 10^{-2}°/hr. In addition, design of the gyroscope is complicated and its load resistance is reduced.

The displacement of the gyroscope may be periodic in nature. In this case far less rigid requirements are set for displacement stability. The periodic displacement may be generated by mechanical swinging of the gyroscope or displacement of the operating point by the optical elements. In the /48
first instance oscillatory motion of a frequency of 10-40 Hz and an

amplitude of several hundred angular seconds is imparted to the gyroscope housing. The true angular displacement of the gyroscope is made up of the angular displacement during one-half of the cycle and is subtracted during the second half on change in the direction of displacement. The integrated output signal of the gyroscope represents the true turning angles.

Elimination of the drag effect by means of a Faraday element. This method of generating the apparent speed of displacement is one of the most commonly used and consists in the following. Over a certain section of the ring laser the two counterbeams 1 and 8 (Figure 15) having linear polarization are converted by means of two quarter waveplates 2 and 7 to beams with opposite (3 and 6 respectively) directions of circular polarization. When the counter-rays pass through magnetoactive medium 4 (glass or quartz, for example), which is in magnetic field 5, the Faraday effect is exerted: the light beams are propagated at different phase velocities. Thus even when there is no gyroscope rotation the counterbeams differ in frequency, and their difference Δf is proportional to the magnetic field value.

The optical path becomes longer in one direction than in the other when such optical elements are introduced into the gyroscope cavity. The operating point of the characteristic thus emerges from the capture zone.

Utilization of the Fresnel-Fizeau drag effect. This method of counteracting the forcing effect also makes it possible to eliminate the need for rotating or oscillating the entire gyroscope. /49

The method consists in introducing a moving optically transparent medium into the resonator. If the liquid used has a refraction index n and rate v, the velocity of propagation of light in this medium is

$$V = \frac{c}{n} + v\left(1 - \frac{1}{n^2}\right),$$

in which $(1 - \frac{1}{n^2})$ is the Fresnel drag coefficient;

c is the velocity of propagation of light in a vacuum.

The partial displacement obtained as the result of flow of the liquid over resonator length l is defined by the formula

$$\Delta f_{\text{сж}} \approx \frac{2lv\,(n^2-1)}{p \cdot n}.$$

Then n = 1.0002926, λ = 0.6328 μ, p = 3 m, l = 0.7 m and v = 1 m/sec, the displacement value is Δf_{sh} = 430 Hz, this exceeding the forcing zone for a gyroscope with a prescribed perimeter.

The difficulty in ensuring a constant flow rate for the liquid and eliminating liquid turbulence must be considered to be disadvantages of this method.

In place of the liquid use may be made of directional drift of the atoms in the active material. This can be accomplished by supplying the resonator with direct current.

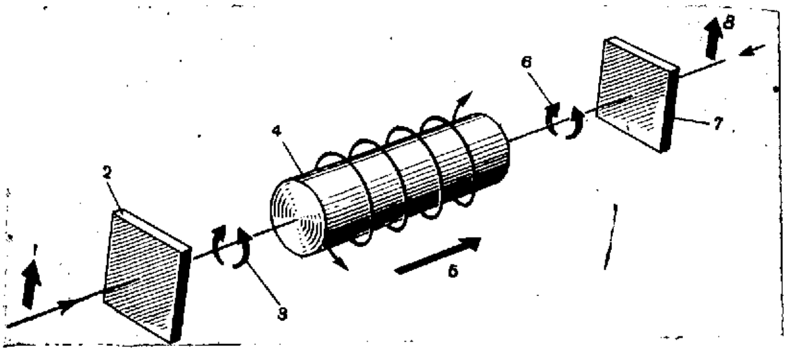

Figure 15. Faraday Element.

2.7. Methods of Increasing Stability of Laser Gyroscope Operation

A highly important factor affecting the stability of gyroscope operation is geometric uniformity of the laser beam optical path.

Optical path instability causes corresponding changes in the laser beam frequencies, influences the frequency forcing effect, and indirectly lowers accuracy of measurement. Thus in the laser gyroscope foreign specialists strive above all to ensure that the optical circuit in which the laser beams are propagated will be uniform.

The use of piezoelectric elements with the mirror or prism forming part of /50
the laser gyroscope light circuit secured on them is proposed for these purposes. The piezoelectric element is controlled by a so-called error signal by means of a tracking system.

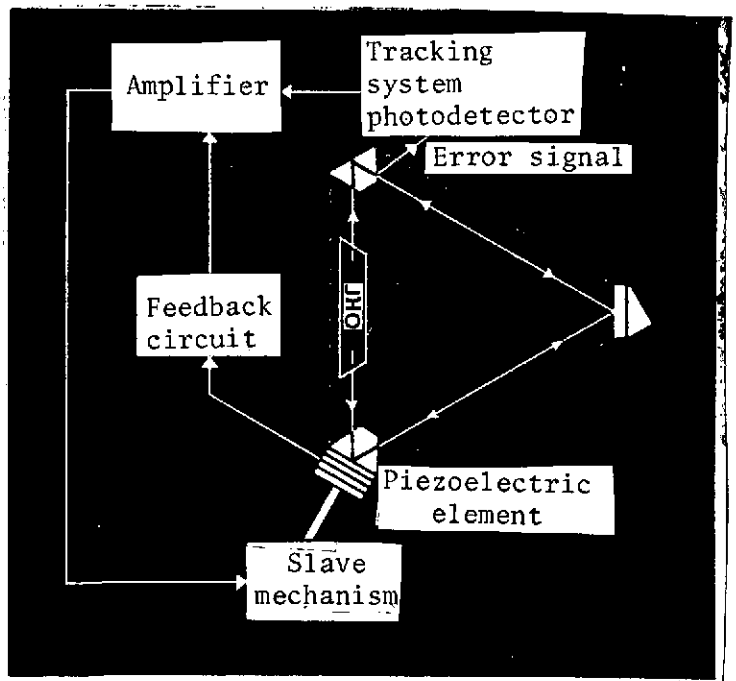

Figure 16. Block Diagram of Compensation for Change in Length of Gyroscope Optical Cavity.

The block diagram of such a system having a piezoelectric element, one proposed by French specialists, is shown in Figure 16.

Change in the length of the gyroscope optical cavity is caused by the occurrence of an error signal corresponding to this change. The error signal is isolated by the tracking system photodetector and acts on a piezoelectric element having /51
a prism mounted on it, through an amplifier and slave mechanism. Thus changes in the optical path of the laser beams are compensated by change in the position of the prism.

Use of this stabilization method has enabled the French to measure the speed of rotation of the Earth with an accuracy of 0.01° for a period of several minutes.

There are other factors as well which affect the accuracy of gyroscope measurement, ones such as instability of the amplification factor of the gyroscope optical circuit and so-called differential losses.

It is the opinion of foreign specialists, however, that in the immediate future the accuracy of measurement by laser gyroscopes will be limited not by the fundamental characteristics of the measurement method but by the technology of gyroscope manufacture, the methods of creating the displacement speeds, and other technical factors.

The progress made in this sphere can be assessed on the basis of foreign laser gyroscope models. While in 1963 a laser gyroscope with a circuit having an area of 1 m^2 had a measurement threshold equaling 50°/hr, by 1967 an optical gyroscope having a circuit area several orders of magnitude smaller was able to measure speeds equaling 0.1°/hr.

It can confidently be stated that the potential for increasing laser gyroscope accuracy is far from having been exhausted and that significant advances can be made in this field.

3. Laser Gyroscope Applications /52

As has already been stated, only experimental laser gyroscopes are known at the present time. It may be assumed, however, that because of their advantages they will be widely used in the near future as sensing elements in automatic control and stabilization systems.

Laser gyroscopes may be used as pickups for the angular velocity of rotation of objects.

Let us first consider the operation of a conventional electromechanical angular velocity pickup. The principle of operation of a device such as this is based on measurement of the gyroscopic moment arising on rotation of a two-stage gyroscope at a definite angular velocity relative to the axis of sensitivity.

The basic diagram of an electromechanical angular velocity pickup is shown in Figure 17.

The basic elements of the pickup are a two-stage gyroscope consisting of a rotor 1, frame 2, spring 3, damper 4, and a device for detecting output signal 5 (in this case a potentiometer pickup).

Axis OY, which is perpendicular to the plane of frame 2, is called the axis of sensitivity or measurement axis (and sometimes is also termed the "input" axis).

Axis OX of the frame, which is the suspension axis, is termed the "output" axis of the instrument.

Axis OZ is the axis of natural rotation of the rotor; kinetic moment vector $\overline{H}$ is oriented along this axis.

A device such as this reacts to an angular velocity the vector of which is /53
perpendicular to the plane of the frame.

Gyroscopic moment M_g arises on rotation of the object on which the angular velocity pickup is mounted about axis of sensitivity OY at angular velocity ω_a. This moment strives to cause kinetic moment vector $\bar{H}$ to coincide with angular velocity vector $\bar{\omega}_a$ over the shortest path. The gyrounit begins to rotate about axis OX in the direction indicated by the broken-line arrow. Spring 3 resisting rotation of the gyrounit is placed under tension, with the result that moment M_{sp} arises.

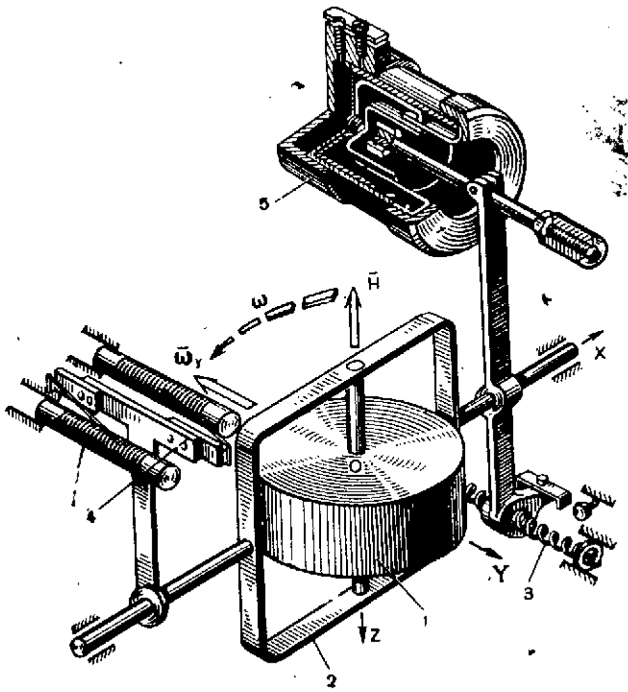

Figure 17. Basic Diagram of Electromechanical Angular Velocity Pickup.

Gyroscopic moment M_g is proportional to the values of H and ω_a, but since kinetic moment H is constant for this particular instrument, the gyroscopic moment value will change only on change /54 in angular velocity ω_a of rotation of the object. When the gyroscopic moment is offset by the moment of the spring, which has been deflected through a certain angle β, stops. Gyroscope deflection angle β will thus be proportional to the velocity to be measured.

The output signal is detected in the form of voltage by potentiometer pickup 5. Damper 4 serves to damp the natural vibrations of the gyrounit.

It is assumed that it will be possible to use laser gyroscopes successfully as angular velocity pickups. Such pickups can be used in autopilots in order to introduce into the control function a signal proportional to the angular velocity, in satellites and spacecraft as the sensing elements of damping devices damping the vibrations of the craft relative to the center of mass, and to limit the angular velocity of rotation of space vehicles when they are oriented. In addition, the laser gyroscope may be used as a compass of high accuracy indicating the direction of the geographic meridian.

It is to be remarked in conclusion that use of the laser gyroscope as a sensing element is not restricted merely to the instruments and systems mentioned in the foregoing.

For example, if an integrator is installed at the laser gyroscope output it is possible to obtain from it a signal proportional to the angle of rotation of the base of the gyroscope installed in the vehicle. The laser gyroscope is thereby converted to an instrument identical in purpose to the integrating gyroscope. Hence the various control systems employing integrating gyroscopes could be considered yet another potential application of the laser gyroscope.

In addition to their use in the orientation and stabilization systems of moving objects, laser gyroscopes may also be used in various branches of the national economy, for example, for measurement of the rate of flow of liquid and gases, measurement of the drift of continents, and so forth.

Let us consider some of the possible systems of application of the laser gyroscope as a sensing element in the automatic control systems of various moving objects. /55

3.1. The Laser Gyrocompass

To determine the direction of movement of an object it is necessary to know its heading, that is, the angle formed by projection of the speed vector of the axis of the object onto the plane of the horizon and the direction of the meridian. Widely varying methods are employed to measure headings: magnetic, gyroscopic, astronomic, and radio methods.

While we will not enter into a discussion of the principles of operation of the directional instruments based on the methods referred to, we can note that not one of them can ensure precise measurement of heading with the various movement parameters and under the different movement conditions. Each of the directional systems has its advantages and disadvantages; the disadvantages of one system to some extent coincide with the advantages of another. For this reason use is made at the present time of composite directional systems combining various course indicators. This presents a number of advantages over separate use of heading instruments.

At the same time, research is in progress to find new heading measurement methods which are even more accurate and dependable and are characterized by higher speed of operation.

For example, it is believed to be possible to use as a compass a device the sensing element of which is represented by a laser gyroscope.

The simplified structural diagram of such a laser gyroscope is presented in Figure 18.

A helium-neon ring laser 1, which is enclosed in a one-piece quartz block, is mounted on flat plate 2. The plate in turn is secured to a metal shaft mounted in bearings 3. The plate holding the laser gyroscope is located at constant speed about the vertical axis by motor 5.

Bearing 6 is mounted on cylindrical housing 4. The inner ring of the bearing is fitted on the housing, and the outer ring is press-fitted into the /56 ringshaped base of bracket 7, on which reference light source 8 is secured. Hence the light source as well can rotate about the same vertical axis. It is rotated by servomotor 9, which is controlled by signals from photomultiplier 10 and the reference light source compared in the phase detector.

Housing 4 is mounted on stage 11, which is enclosed in gimbals and is stabilized in the horizontal plane by means of roll and pitch control signals taken from the central vertical gyroscope.

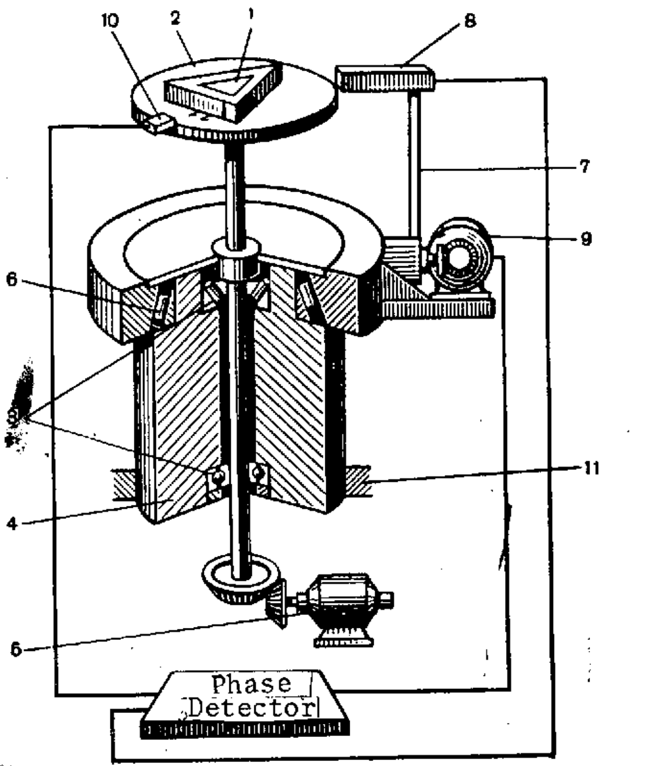

Figure 18. Structural Diagram of Laser 6 Year Old Compass.

Let us examine briefly the principle of operation of such a /57
gyroscope.

As we know, the beat frequency of the light signal of a ring laser is proportional to the angular velocity Ω of its rotation, the vector of which coincides with the direction of the axis of sensitivity of the laser gyroscope. The axis of sensitivity of the laser gyroscope is in this case situated in the plane of the horizon and is perpendicular to the plane of plate 2. The angular velocity measured by the gyroscope is the projection of the horizontal component of the vector of terrestrial rotation u_h onto the direction of the axis of sensitivity of the gyroscope. The direction of the axis of sensitivity is determined by the position of plate 2 in the azimuthal plane. The horizontal component of vector u_h of terrestrial rotation in this case coincides with the direction of the meridian. In the design in question the plate holding the gyroscope is rotated by motor 5, which is also mounted on a stabilized stage, at a constant angular velocity about the vertical axis, which is perpendicular to the axis of sensitivity. The signal taken from the gyroscope will be at the maximum when the plate in its rotation assumes a position perpendicular to the vector of the horizontal component of terrestrial rotation, and at the minimum when the plate is in a position parallel to the vector of the horizontal component of terrestrial rotation (at the equator).

Thus when plate 2 is rotated at constant speed the signal obtained from the laser gyroscope becomes frequency modulated. The modulation period corresponds to the speed of rotation of plate 2. The modulated vibrations from the electron phase multiplier are detected by a discriminator, from the output of which a sine wave voltage of the modulation frequency is taken.

The reference light source situated around the axis of rotation emits a light pulse whenever this beam is perpendicular to the plane of plate 2. These pulses are fed to a phase detector for separation of the phases of the discriminator output voltage.

Time diagrams clarifying the foregoing are shown in Figure 19.

The phase detector may be used to measure the phase between the reference pulse and the extreme values of the discriminator output signal. If the beams from the reference light source is not parallel to vector u_h, that is, its direction does not coincide with the direction of the meridian (the phase between the extreme value of the signal and the beginning of the reference pulse does not equal zero), an error signal is taken from the integral phase detector output in the form of voltage the value and sign of which depend on phase φ_0 between the extreme values of the signal and the reference pulse. But at the same time φ_0 is the angle between two consecutive plate positions, the first corresponding to the moment in time at which the perpendicular to the plate does not coincide with the direction of the meridian (Figure 19a) and the second to the time at which it does coincide with the direction of the meridian (Figure 19b). /58

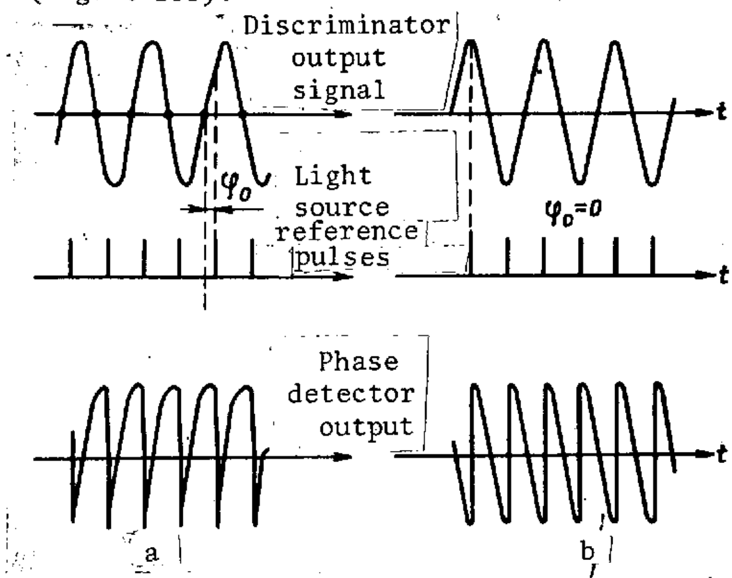

Figure 19. Time Diagrams of Laser Gyrocompass Signals: a, Beam from light source does not coincide with direction of magnetic meridian; b, Beam from light source coincides with direction of magnetic meridian.

The voltage from the phase detector output is fed to a servomotor, which establishes the beginning of reference, that is, it rotates the light source until the error signal from the phase detector output becomes symmetrical in shape (at $\varphi_0 = 0$). The light beam then coincides with the direction of vector u_h and indicates the direction north.

The basic errors for this instrument are systematic ones due to inaccuracies in the periods of rotation of the plate due to defects in the shaft and bearings. However, these errors can be reduced and even completely eliminated by careful adjustment if the dynamic measurement method is abandoned, that is, if the plate is not rotated about the axis parallel to the plane of the laser. /59

With the static measurement method, however, the time required to determine direction north is greatly increased.

Use of the laser gyroscope in directional systems permits considerable improvement in their characteristics as regards accuracy of determination of heading and speed of operation.

3.2. Angular Velocity Pickups in the Autopilot System

As we know, autopilots are devices which automatically control an aircraft or winged missile, ensuring flight along an assigned path. Autopilots not only eliminate the harmful effect of external perturbing factors (such as wind) but can also modify the flight conditions of the craft in accordance with the principle required.

The operation of an autopilot system is based on the principle of angular stabilization of an aircraft. Signals proportional to the angular deflections act on the controls, which stabilize the aircraft relative to the center of gravity, that is, in heading, roll, and pitch (Figure 20).

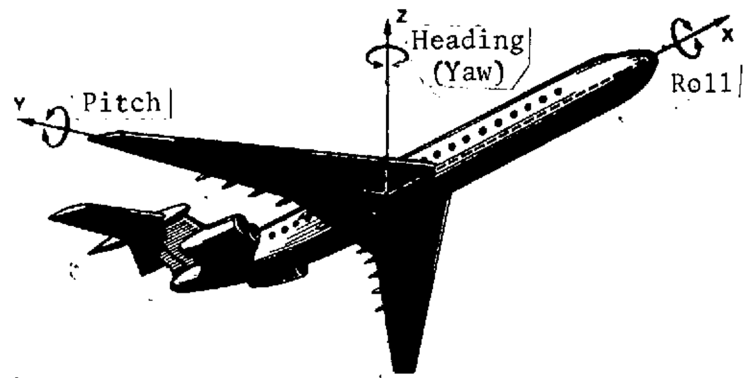

Figure 20. Angular Deflections of Aircraft Relative to Its Center of Gravity.

At the present time instruments based on electromechanical gyroscopes with three degrees of freedom are still used as sensing elements reacting to the angular deflections of an aircraft. They are usually the central vertical gyroscope (CVG) and the directional gyro (DG). The CVG stabilizes the aircraft in the plane of the horizon (roll and pitch), and the DG performs course stabilization. /60

When necessary the heading, roll and pitch angles may be modified in keeping with the flight itinerary, which is assigned by a program mechanism.

The structural diagrams of the heading, roll and pitch control systems are similar, and for this reason we will discuss only one of them.

Figure 21 presents a simplified structural diagram of the automatic pitch control system of an airplane.

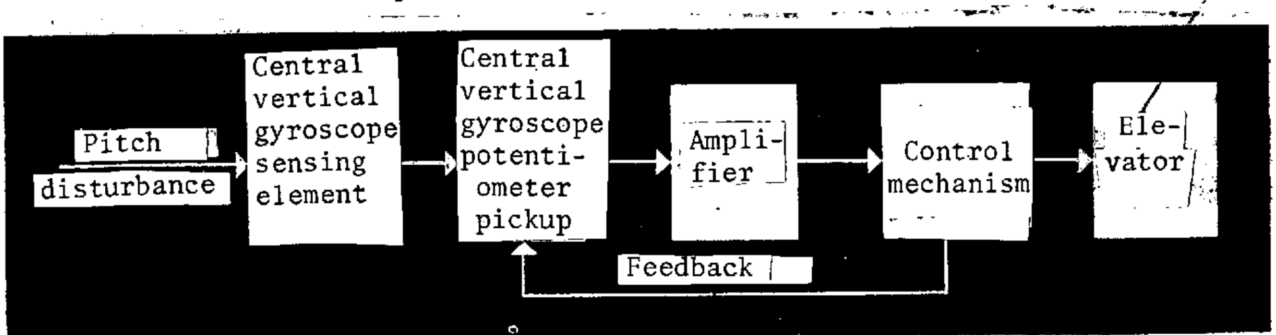

Figure 21. Simplified Structural Diagram of Pitch Stabilization of an Airplane.

When the airplane is deflected from the assigned position (pitch disturbance) a signal proportional to the angular deflection of the aircraft about the OY axis and taken from the CVG potentiometer pickup enters an amplifier. The amplified signal is fed to the electric motor of the control mechanism, which deflects the elevator in the required direction. /61

There is fed from the feedback pickup (usually a potentiometer situated on the rudder mechanism cable drum) to the input of the CVG potentiometer pickup a signal proportional to the angular velocity of movement of the rudder mechanism drum. The signal is out of phase with the control signal from the CVG (negative feedback), as the result of which the total current at the amplifier input equals zero when the rudder mechanism reaches a speed of rotation corresponding to the value of the control signal. The elevator is deflected through a certain angle and the aircraft begins to be returned to the assigned direction of flight by the action of its aerodynamic properties.

The control signal drops at the amplifier input and the elevator begins to assume the former position. The elevator is in the neutral position after the aircraft has returned to the initial position.

An aircraft of high mass, however, does not stop in this position but passes through it as the result of inertia and is deflected in the other direction relative to OY axis. The autopilot again begins to return the aircraft toward the OY axis. Oscillations are thus involved in the process of return of an aircraft to the initial position. These oscillations greatly impair the stability of the aircraft, render control of the craft difficult, and may even lead to a crash at high speeds of flight.

In order to reduce such oscillations of an airplane it is necessary to apply in deflection of the control surfaces a certain lead which depends on the value and direction of the angular deflection. This lead can be created by means of special automatic devices called dampers.

In order to obtain the lead the sensing element of the damper must react to the angular velocity of turn of the aircraft. Introduction into the autopilot control system of a damping signal proportional to the angular speed greatly improves its characteristics and vibrational stability.

Laser angular velocity pickups, the signals of which are proportional with high accuracy to the angular speeds of an aircraft, may be successfully used as the sensing elements of a damper. /62

Depending on the position of the axis of sensitivity the laser angular velocity pickup will react to the angular speed of rotation of an aircraft relative only to one specific axis (for example, OX, OY or OZ).

Depending on the angular velocity sensed by the angular velocity pickup and the aircraft axis relative to which the damper damps vibrations, a distinction is made between roll dampers (relative to the OX axis), yaw dampers (relative to the OZ axis), and pitch dampers (relative to the OY axis).

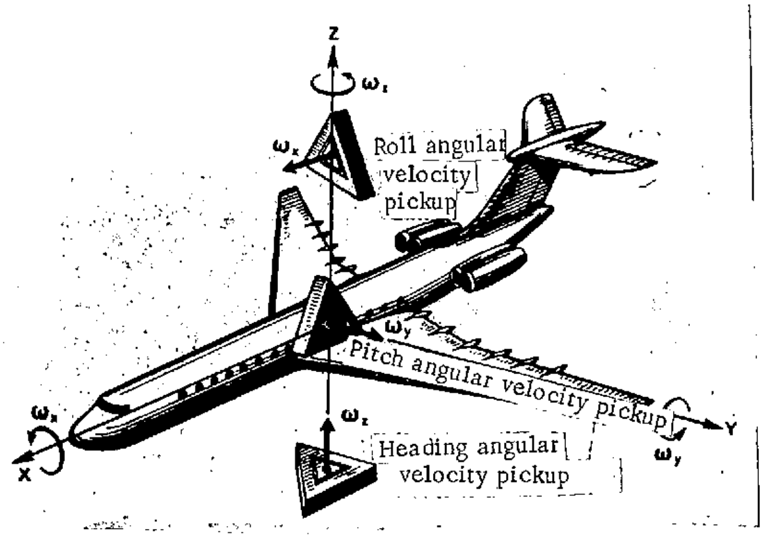

Figure 22. Mounting of Laser Angular Velocity Pickups for Measurement of Angular Speeds of an Aircraft.

The mounting of three laser angular velocity pickups on an aircraft for measurement of angular speeds ω_x, ω_y and ω_z of its rotation relative to all three axes is illustrated in Figure 22.

Foreign specialists believe that it will be the most efficient to use a two degree of freedom one-piece laser gyroscope block in the autopilot for damping of an aircraft relative to three axes.

Let us consider (Figure 23) the principles of operation of the damping device of an autopilot on the basis of one of the channels (such as the pitch channel). The operation of this device is analogous to that of the corresponding control channel of an autopilot using electromechanical gyroscopes. /63

When the aircraft assumes angular speed ω_y of turn, laser angular velocity pickup 1 emits a signal proportional to this speed. The signal is amplified in an amplifier and fed to the bonding of power relay 3, which operates and feeds the aircraft power supply voltage to electric motor 4 of control mechanism 6. Cable drum 5 of the control mechanism deflects the elevator in the required direction to offset the growing angular speed of deflection of the aircraft.

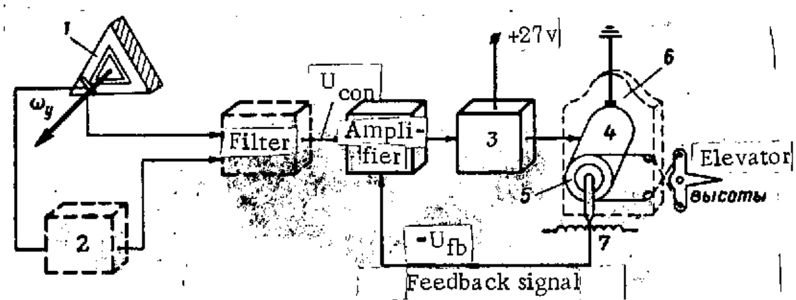

Figure 23. Diagram of Autopilot With Damping Device (Pitch Channel).

In rotating, cable drum 5 of the control mechanism moves feedback potentiometer brush 7 secured on it, with the result that feedback signal U_{fb} enters the amplifier. This signal, being added to signal U_{con} from the laser angular velocity pickup, causes timely halting of the movement of the cable drum when $U_{con} - U_{fb} = 0$.

In some instances the aircraft control conditions require the introduction of a signal proportional to the angular acceleration of the aircraft as well as a signal proportional to the angular speed of turn. In this case the output signal of the laser angular velocity pickup is fed to the amplifier through differentiator 2. In order that the operation of the damper will not affect the maneuverability of the aircraft, its circuit includes a special filter passing to the amplifier only the alternating component of signal ω_y occurring during aircraft oscillations.

The damping devices for the other two axes of rotation of the aircraft are similar in structure. /64

3.3. The Laser Gyroscope in the Orientation System of a Space Vehicle

The control systems of space vehicles are usually designed to ensure orientation and stabilization of the vehicle's position on the flight path in interplanetary space or in the orbit of an Earth satellite vehicle.

In design principle such systems (like the autopilots) are closed control systems incorporating the object controlled (space vehicle), measuring (sensing) devices, which emit information on the parameters of movement of the vehicle, amplifying, converting and logic devices, which establish the required conditions of control of the vehicle's movement, and slave devices which create the necessary forces and moments.

The slave devices employed in such systems to modify the orientation of a space vehicle may be conventional and vernier (gimbaled) jet engines, governor engines representing rotating masses of great kinetic moment, and special devices utilizing the magnetic field of the Earth or the energy of solar radiation.

Laser gyroscopes may be successfully used as the sensing elements of the automatic control systems of space vehicles along with electromechanical gyroscopes, phototracking measuring systems, and various astro systems. Because of their superior features the gas lasers can simplify existing control systems and substantially increase their accuracy.

Let us consider one of the various automatic systems for orientation of solar battery units permitting maximum utilization of the energy of the Sun's rays.

A system such as this consists of a photoelectric solar pickup, three laser angular velocity pickups, an amplifier-converter unit, a logic system, and slave devices (small jet engines). By means of this system the solar batteries /65 are oriented by comparison of the signals from the photoelectric pickup and the laser angular velocity pickups in the logic unit.

The photoelectric solar pickup, which is mounted in fixed position on the surface of the solar batteries, emits a signal of the relay type ("yes-no"), indicating whether the corresponding field of view of the pickup has been illuminated or not. Hence the photoelectric pickup in the control system is used to search out the Sun, since the solar batteries may initially be in any position. After the batteries have been positioned in the area of space illuminated by the Sun, the vehicle is kept in the oriented position by the combined operation of a photoelectric pickup and laser gyroscopes.

The slave devices (small jet engines) provide constant thrust when they are switched on. They may only be either switched on or switched off; in addition, the logic unit may also determine that the engines will operate under pulse conditions.

Let us consider the operation of the system in orientation of a space vehicle relative to one of the axes (for example, the Z axis), assuming that the batteries have already been oriented toward the Sun along the other two axes. The basic diagram of such an automatic system is shown in Figure 24.

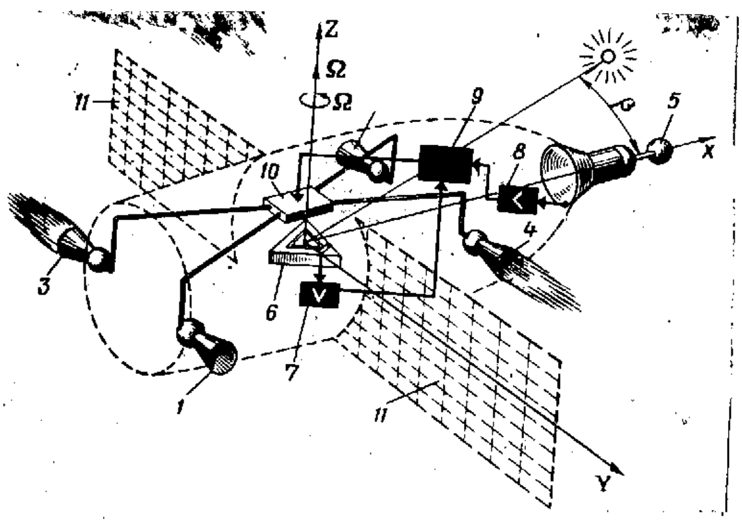

Figure 24. Diagram of Orientation of Solar Batteries on Space Vehicles by Means of Laser Angular Velocity Pickups.

It should be noted that laser angular velocity pickup 6 may in this case operate in the search mode and in the ordinary speed indicator zero mode. In the first case the laser angular velocity pickup has a coarsened threshold of sensitivity to the value of Ω_0 (the sensitivity threshold is the minimum angular velocity ω_{min} which the instrument can measure); in the second case the laser angular velocity pickup operates in the ordinary mode, and then its sensitivity threshold corresponds to ω_{min}. /66

When the Sun is absent from the field of view of photoelectric pickup 5, an instruction signal for orientation along the Z axis enters logic unit 9 of the control system. After it has been converted the instruction signal enters the electromagnet of slide-valve device 10, which starts the jet engines (1 and 2, for example), ensuring rotation of the space vehicle about the Z axis at constant angular velocity Ω. Laser angular velocity pickup 6 in this instance operates in the first mode.

When the angular velocity of rotation of the space vehicle about the Z axis reaches value Ω_0, the logic unit switches off engines 1 and 2 and rotation of the space vehicle then continues by inertia.

After the Sun has entered the field of view, the photoelectric pickup generates a signal which is amplified in amplifier 8 and delivered to logic unit 9. The logic unit in turn switches on engines 3 and 4, which operate in the continuous mode and bring about rapid braking of the space vehicle. At the same time, the logic unit switches laser angular velocity pickup 6 to the speed indicator zero mode, removing displacement Ω_0 of the sensitivity threshold.

When the absolute angular velocity of rotation of the space vehicle about the Z axis decreases to the value equaling the upper boundary of the insensitivity zone plus Ω_1, the logic unit switches engines 3 and 4 to the pulse mode of operation. After displacement angle β decreases to the value corresponding to the lower boundary of the insensitivity zone minus Ω_2, the logic unit switches off engines 3 and 4. The vehicle then continues to rotate by inertia at an angular velocity near $-\Omega_2$, and finally the Sun leaves the field of view of the photoelectric pickup.

The orientation system resumes the search for the Sun, the laser angular velocity pickup is switched to the first mode of operation (displacement Ω_0 is /67 again delivered to it). Since angular velocity Ω_2 of the space vehicle is low, the latter does not have time to undergo substantial deflection from the Sun. For this reason the Sun virtually immediately enters the field of view of the photoelectric pickup and the entire orientation process in question is repeated, but now is characterized by an oscillatory process of very small amplitude.

Thus there is established a mode of oscillation of the space vehicle about the Z axis which is characterized by angular velocities near the sensitivity threshold of the laser angular velocity pickup (the angular velocities in this case will not exceed 0.01-0.001°/hr). In addition, the oscillations will take place at the boundary of the field of view of the photoelectric pickup, at values of angle β very near zero.

It is to be expected that in the very near future laser angular velocity pickups will become an integral component of the automatic orientation and stabilization systems of space vehicles. In addition, laser angular velocity pickups can be used as the basic sensing elements of inertial navigation systems ensuring orientation and stabilization of a space vehicle in all stages of flight.

3.4. The System of Indirect Stabilization Controlled by Angular Velocity Pickups

Indirect stabilization is a system in which a particular device (gun, sight, telescope) is stabilized by means of servomotors controlled by gyroscope signals. In this case the properties of the gyroscopes as gyroscopes are not used directly for stabilization. The device is in this instance said to be mounted on a stabilizing stage.

The gyroscopic elements are used in this case only to form signals entering amplifiers which control stabilizing engines. The latter in turn rotates the stage so that its position does not change in space.

In the past one-axis electromechanical gyroscopes have generally been used as the sensing elements in such stabilizers. At the present time use may also be made of laser angular velocity pickups.

Figure 25 illustrates the two-axis indirect stabilizer of a ship's telescope in which laser gyroscopes are used as sensing elements.

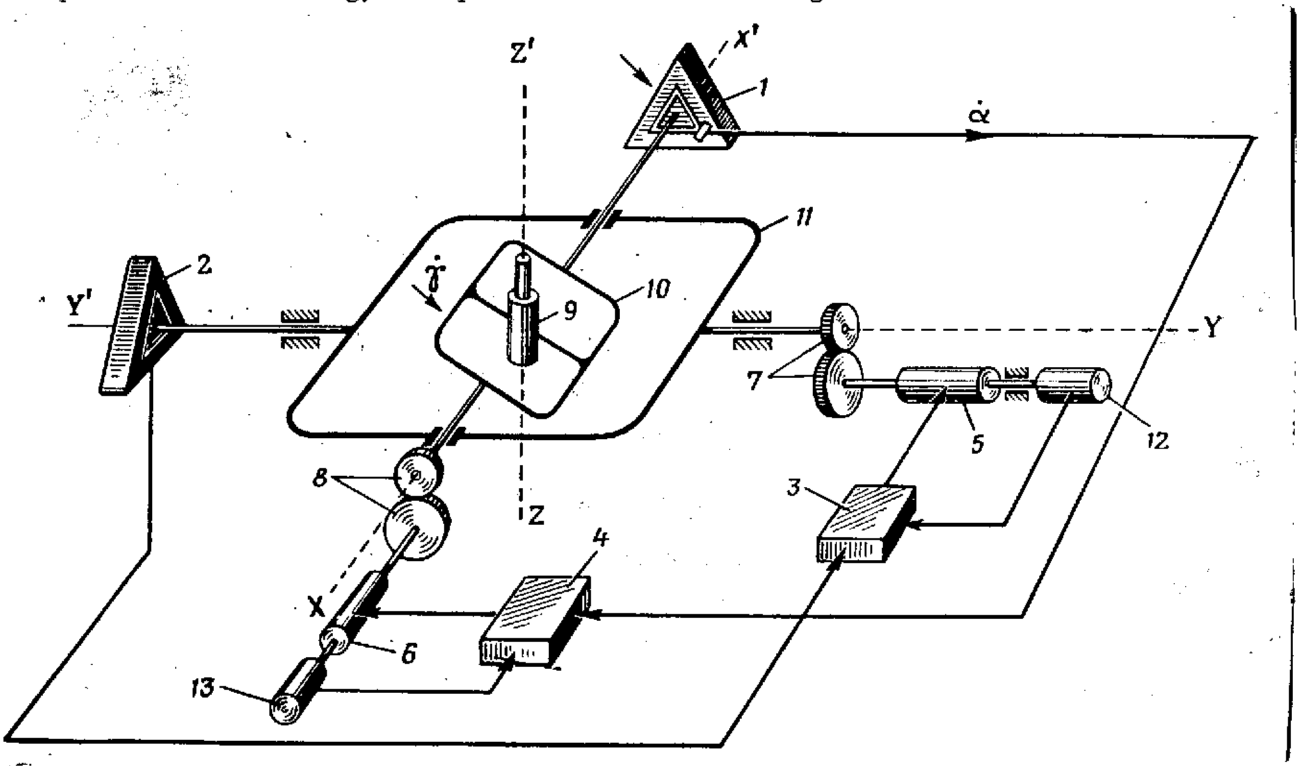

Figure 25. Diagram of Indirect Ship's Telescope Stabilizer Using Laser Angular Velocity Pickups.

In this stabilizer the laser angular velocity pickups generate control signals proportional to the absolute angular velocities of rotation of the stage about axes XX' and YY'. /69

Since rotation of the telescope about the direction to a star (about the ZZ' axis) is unimportant, stabilization is carried out only with respect to two axes.

Let us consider the principle of operation of such a stabilizer relative to one axis, for example, XX'.

When the ship rolls at angular velocity $\dot{\Theta}$ the stage on which telescope 9 is mounted (in this case the inner frame of gimbals 10) turns relative to the rolling vessel at angular velocity $\dot{\gamma}$. The absolute angular velocity of the stage relative to the inertial space, which velocity is measured by laser angular velocity pickup 1, is:

$$\dot{\alpha}=\dot{\Theta}-\dot{\gamma}.$$

A signal corresponding to this velocity enters amplifier-converter device 4. An amplified signal proportional to the angle of rotation of the stage relative to the XX' axis is taken from the output of this device. The signal then enters motor 6 which moves the stage by means of reducing gear 8 to the original position.

Tachogenerator 13, which is rigidly connected to the motor, is used to compensate the signal coming from angular velocity pickup 1 to the amplifier--converter unit on movement of the stage to the original position.

The telescope is stabilized relative to the YY' axis in a similar manner.

Conclusion /70

It has of course been impossible in this pamphlet to consider all the theoretical questions associated with laser gyroscopes and to discuss their practical applications in detail. And although the laser gyroscopes even now possess fairly good technical characteristics, the scientists of many countries are continuing their research in this field. Further improvements are being made in laser gyroscopes each year; their size and weight are being reduced and their accuracy is being increased. The sphere of application of laser gyroscopes is becoming increasingly wider.

But it should by no means be inferred from what has been said that gyroscopes based on other principles of operation should not be used. Electrostatic, molecular, and vibrational gyroscopes afford very good prospects. The future belongs to the instruments being brought into existence today.

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